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Transgressive sedimentation in rift-flank region: Deposition of the Endicott Group (early Carboniferous), northeastern Brooks Range, Alaska

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TRANSGRESSIVE SEDIMENTATION IN RIFT-FLANK REGION: DEPOSITION OF THE ENDICOTT GROUP (EARLY CARBONIFEROUS), NORTHEASTERN BROOKS RANGE, ALASKA

A

THESIS

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TRANSGRESSIVE SEDIMENTATION IN RIFT-FLANK REGION: DEPOSITION OF THE ENDICOTT GROUP (EARLY CARBONIFEROUS), NORTHEASTERN BROOKS RANGE, ALASKA

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ABSTRACT

In the range-front region of the northeastern Brooks Range, the Endicott Group overlies a regional angular unconformity (sub-Mississippian unconformity) and consists of a relatively well-exposed transgressive fluvial succession at its base (Kekiktuk Conglomerate) and a gradational terrigenous clastic-to-carbonate transition at its top (Kayak Shale). Thirty-one stratigraphic sections were measured to characterize the sedimentology, paleogeography, and tectonic setting of the Endicott Group. Just prior to latest Tournaisian-earliest Visean time, the range-front region was characterized by fluvial incision. Fluvial incision throughout the region was followed in latest Tournaisian-earliest Visean time by fluvial deposition in incised paleovalleys, which were gradually filled and superseded by marginal- and shallow-marine environments (Kayak Shale) as transgression progressed. The limited thickness, widespread distribution, and organization of the Kekiktuk Conglomerate, combined with its stratigraphic position above an angular unconformity and below marginal- and shallow-marine shales, suggests deposition in an upland, rift-flank region landward of the tectonic hinge zone on a passive continental margin.

Widespread but volumetrically minor coal in the Kekiktuk Conglomerate combined with plant spores and abundant plant fragments in the Kayak Shale suggest that the coastal zone and some valley bottoms were heavily vegetated and that the range-front region was in a humid climatic zone during latest Tournaisian-Visean time. Large volumes of terrestrial organic material were subsequently transported into shallow-marine environments and resulted in a widespread oxygen-depleted bottom-water layer. Regional stratigraphic studies indicate that widespread carbonate sedimentation (Lisburne Group) began south and southwest of the range-front region in late Tournaisian time, which suggests conditions of restricted circulation

probably existed in marine environments toward the north, in the range-front region, and promoted oxygen-deficient conditions.

The upper Kayak Shale records a gradational transition from terrigenous clastic-dominated environments below to carbonate-dominated environments above (Lisburne Group). Superimposed on this transition are small-scale terrigenous clastic-to-carbonate transitions recorded in meter-scale parasequences and acyclic successions. The stratigraphic and geographic distribution of parasequences and acyclic successions reflects their paleogeographic position with respect to the strand line and terrigenous clastic sources. The humid climate, low paleolatitude, and tectonic setting (upland rift-flank region) were first-order controls on the terrigenous clastic-to-carbonate transition recorded in the upper Kayak Shale.

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ACKNOWLEDGEMENTS

When I decided to pursue doctoral studies in sedimentology at the University of Alaska, I was motivated by a strong interest in the field and, in particular, an overwhelming desire to live in Alaska and work in a remote region such as the Brooks Range. I had only a vague idea of the sort of research I wanted to pursue and no idea of the enormous personal commitment (in time and effort) required to complete a dissertation project. Although a strong personal commitment was fundamental, this project would not have been possible without the support of a number of organizations and individuals.

This project was conceived by Drs. Keith Crowder, Wes Wallace, and Keith Watts, all of whom at the outset had an appreciation for the importance of the Endicott Group in unravelling the Early Carboniferous history of Arctic Alaska. Keith Crowder chaired my research committee and introduced a neophyte sedimentologist who was literally wet behind the ears (from studying water saturated and contaminated dirt in New England) to the complexities of Endicott geology. During subsequent years, Keith was always willing to spend time with me both in and out of the field and lend a helping hand wherever and whenever it was needed. Wes Wallace and Keith Watts served on my research committee, provided constructive advice throughout the project, and were always willing to discuss any aspect of Brooks Range geology. All three contributed significantly to the dissertation manuscript through their editorial efforts. The final product is significantly better than it would have been without their input.

Drs. John Decker (ARCO Alaska) and Paul Layer (Geophysical Institute, University of Alaska) rounded out my reseach committee. Even though his schedule was always full and work/living location nearly 400 miles away, John Decker generously provided his petrographic and editorial expertise.

I sincerely appreciate the efforts of Drs. John Utting (Geological Survey of Canada) and Anita Harris (U.S. Geological Survey), who provided their expertise in palynology and conodont biostratigraphy, respectively, at no charge. In particular, John Utting processed and analyzed 78 palynologic samples collected from outside Canada and gave his expertise freely in numerous conversations. I gratefully acknowledge the Canadian Geological Survey for providing John's expertise free of charge.

I gratefully acknowledge Jim Clough, Charles (Gil) Mull, Rocky Reifenstuhl, and Mark Robinson of the Alaska Division of Geological and Geophysical Surveys (ADGGS) who provided invaluable advice. In particular, Jim Clough and Dr. Robert Blodgett (U.S. Geological Survey) saved myself and field assistant from certain starvation at the beginning of the 1989 field season by providing a can of Blazo. In return they only demanded a photograph of myself with above mentioned can (to be used at some later date for blackmail and extortion).

Through the course of three and half field seasons, I was very fortunate to have had excellent field assistants. Karen Adams helped me measure a section of Endicott Group along Leffingwell Fork during my 1988 Endicott introduction. Karen's approach to measuring and recording stratigraphic sections helped prepare me for subsequent field seasons. My sister, Laurie, provided slave labor and companionship during the 1989 season; Craig Schneider provided slave labor, geological expertise, and companionship during the 1990 season; and a second sister, Andrea, provided slave labor and companionship during the 1991 season. These people provided muscle, encouragement, sweat and, quite often, blood for minimal financial gain. Without their efforts, I would not have covered the geographic area that I did, and the time spent in the field would not have been as enjoyable.

I wish to thank present and past graduate students at the University of Alaska, notably Arlene Anderson, Jim Clough (also of ADGGS mentioned above), Paul Gruzlovic, Cathy Hanks, Tom Homza, Andrea Krumhardt, Mark Myers (also of Alaska Division of Oil and Gas), and Sue Morgan for many thought-provoking discussions on the Endicott and Lisburne Groups and geology of the Brooks Range. Andrea Krumhardt provided her expertise to process and pick conodont samples. In particular, I gratefully acknowledge Mark Myers for offering freely his professional expertise in terrigenous clastic depositional systems, and Arlene Anderson for her expertise on the Devonian-Carboniferous geology of the Brooks Range. All of these people provided invaluable moral support throughout the project.

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Finally, I wish to thank my wife Joan, and son Kerry, for their moral support throughout this project. Over the course of four summers in Alaska, we were only able to enjoy one of them together (1992) due to my field work in ANWR. Joan was always supportive, rarely complained, and sent care packages loaded with essential supplies on numerous occassions. Kerry, (age 2 1/2 years) provided moral support by being a continuous source of amazement and joy. Without Joan's financial support and encouragement I would not have been able to pursue this research.

CHAPTER 1: INTRODUCTION

Stratigraphic cross-sections from passive continental margins typically show a wedge of sediment that thickens abruptly seaward of the tectonic hinge zone. This wedge develops during the post-rift or drift phase of passive continental margin evolution, when thinned continental crust cools and sinks in a process known as thermally controlled subsidence (Steckler and Watts, 1982). Most cross-sections that extend far enough in the landward direction show a transgressive succession that thins to a feather-edge a significant distance landward of the tectonic hinge zone (e.g. Dewey and Bird, 1970; Symonds et al., 1983). These landward-thinning successions develop where subsidence rates are lower than those associated with thinned continental crust seaward of the tectonic hinge zone, due to the flexural rigidity of the unthinned continental crust landward of the tectonic hinge zone (Steckler and Watts, 1982). Detailed examples of early post-rift successions deposited in this position are not common in literature on passive continental margins (e.g. Allen and Allen, 1990; Mitchell and Reading, 1986). In northern Alaska, the Carboniferous Endicott Group is a well-exposed example of a post-rift transgressive succession that was deposited landward of the tectonic hinge zone, over a rift-flank unconformity. The Kekiktuk Conglomerate and Kayak Shale, assigned to the Endicott Group, are excellent examples of a transgressive fluvial succession and a terrigenous clastic-to-carbonate transition, respectively, whose deposition was strongly influenced by their paleogeographic position in a rift-flank region.

Terrigenous clastic and carbonate rocks of the Ellesmerian sequence (Figure 1-1) in the northeastern Brooks Range of Alaska were deposited on a south-facing passive continental margin during Early Carboniferous to Early Cretaceous time (Bird and Molenaar, 1987). The base of the Ellesmerian sequence is made up of the Kekiktuk Conglomerate and

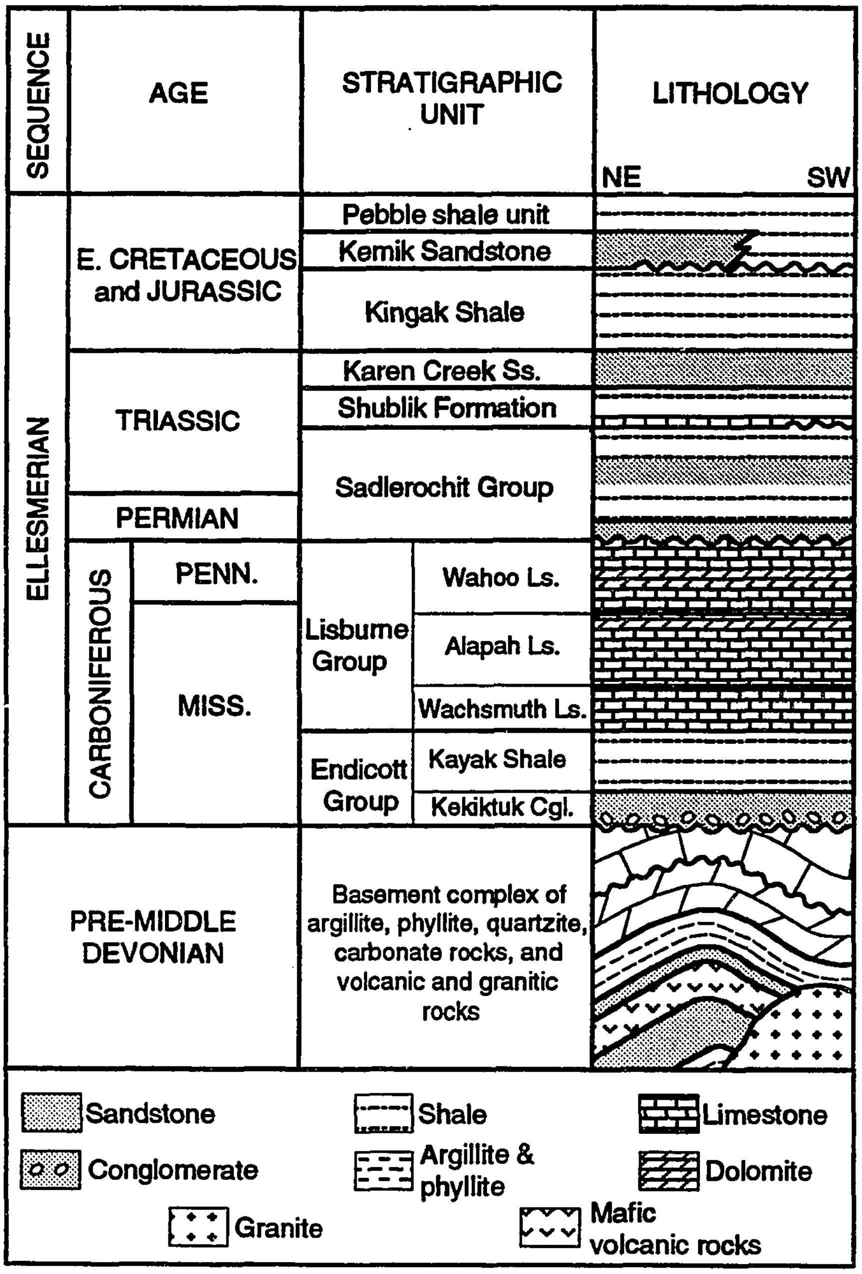

Figure 1-1 - Generalized column of the Ellesmerian sequence in the northeastern Brooks Range. No scale intended. Modified from Bader and Bird (1986).

Kayak Shale of the Endicott Group (Figure 1-2), a widespread transgressive succession whose regional distribution records increasing accommodation due to relative sea-level rise. In the northeastern Brooks Range, the Endicott Group is situated above a regional angular unconformity that represents a hiatus of at least 30 Ma (DNAG time scale - Lower Devonian below and latest Tournaisian-earliest Visean above; Blodgett et al., 1991; Utting, 1991b) and is referred to herein as the sub-Mississippian unconformity. The sub-Mississippian unconformity most likely records the transition from dominantly contractional tectonics below to extensional tectonics above, followed by thermally controlled subsidence (Anderson and Wallace, 1991; Moore et al., 1992).

This Ph.D. dissertation addresses two fundamental questions: 1) what are the regional controls on fluvial depositional systems at the base of transgressive successions on passive continental margins, and 2) what are the major controls on terrigenous clastic-to-carbonate transitions on passive continental margins. In a broad sense, the first question asks how the transition is made from a regional erosional regime to a regional depositional regime. The second question is one that many sedimentologists are trying to address. There are detailed bodies of knowledge on both clastic and carbonate depositional systems, yet we know little about the transitions between these systems. This is surprising since terrigenous clastic-to-carbonate transitions are common in the geologic record and in modern settings.

To address these fundamental questions, this study focused on answering the following more detailed questions: 1) what is the range of lithologies that make up the Endicott Group and how are they organized geographically and stratigraphically throughout the range-front region of the northeastern Brooks Range, 2) what were the paleogeographic and depositional settings for the Endicott Group, 3) what were the dominant controls on deposition of the Endicott Group, 4) what was the tectonic setting of the range-front region

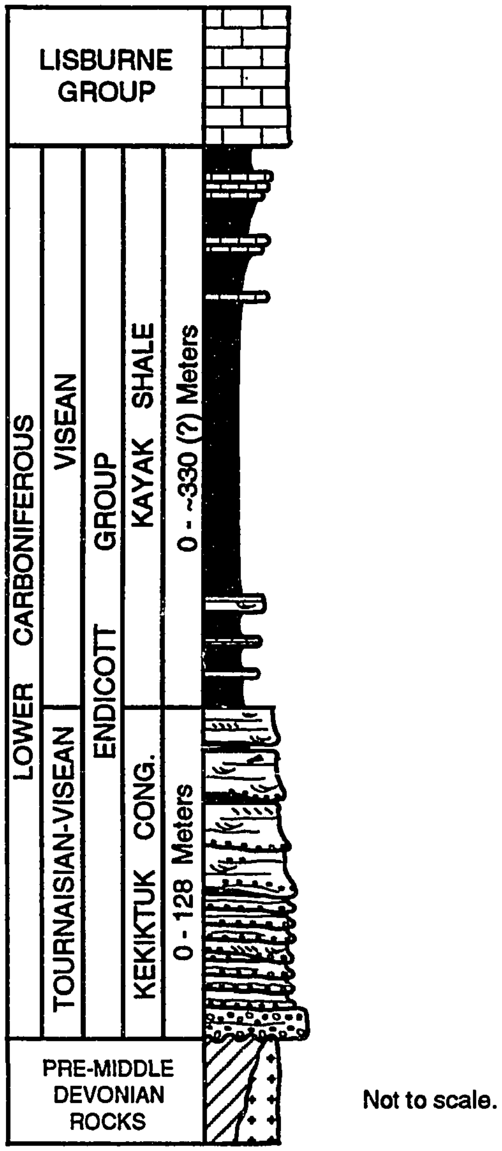

Figure 1-2 - Generalized columnar section of the Carboniferous Endicott Group in the northeastern Brooks Range, Alaska.

during Early Carboniferous time. The results of this study are presented in three manuscripts that will be sent to professional journals for publication.

These manuscripts form the core of the dissertation document (chapters 2, 3, and 4). Chapter 2 addresses the distribution, organization, and fluvial style of the Kekiktuk Conglomerate and its tectonic significance. Chapter 3 addresses the distribution, organization, depositional setting, and significance of marginal-marine rocks in the lower Kayak Shale. Chapter 4 focuses on the terrigenous clastic-to-carbonate transition recorded in the upper Kayak Shale by addressing its organization, depositional setting, and major controls on the transition.

Additional data are presented in the appendices and include the location of all measured sections obtained in this research, biostratigraphic summary tables for palynologic and conodont data, summary tables of sandstone modal analyses, porosity and permeability measurements from selected lithologic samples, total organic carbon data from selected shale samples, and selected measured sections. Thirty-one measured sections were obtained in this study and have previously been released as public data files with the State of Alaska Division of Geological and Geophysical Surveys (LePain and Crowder, Public Data Files 89-1e, 90-19, 91-11, and 92-5). Eleven of the thirty-one measured sections are included in appendix F of this document. These eleven sections were obtained at locations where the Endicott Group is particularly well-exposed and, hence, have served as the primary database for reconstructing the depositional history of the Endicott Group in the range-front region. Data presented in tabular form in appendices C and D were generated through the course of this study and are not discussed in the dissertation document.

STUDY AREA AND METHODS

This project was a field-oriented study of the Endicott Group in the Arctic National Wildlife Refuge (ANWR) of northeastern Alaska. The study area is situated between the range front and the south side of T3S (Mt. Michelson and Demarcation Point quadrangles, ~69°7' north latitude), and is bounded by the Canning River to the west and the Canadian border to the east (Figures 1-3 and 1-4). The study area encompasses about 12,000 km^2 of remote, mountainous terrain that is only accessible by fixed-wing aircraft and helicopter. There are no roads in ANWR. The nearest road is the Dalton Highway, which is ~125 km west of the Canning River. A helicopter was used to reach remote locations in the study area, with time purchased at cost from the U.S. Fish and Wildlife Service.

Field work was conducted during the summers of 1988, 1989, 1990, and 1991 from remote spike camps in the refuge. Stratigraphic sections were measured through the Endicott Group using a Brunton compass and a Jacob's staff and the succession of lithologies, grain types and size, sedimentary structures, bed thickness, and lateral variations were recorded. Lithologic samples were collected for thin-section analysis. Palynologic and conodont samples were collected for biostratigraphic control. Thin-sections were examined to determine composition of terrigenous clastic samples and a limited suite of sandstones (a total of 28) was point-counted to determine detrital modes. A large suite of carbonate rocks from the upper Kayak Shale was examined in detail to determine mineralogic and skeletal grain composition and microfacies.

REGIONAL GEOLOGIC SETTING

In northern Alaska, a regional sub-Carboniferous angular unconformity has been recognized throughout the North Slope subsurface and at widely spaced locations across the

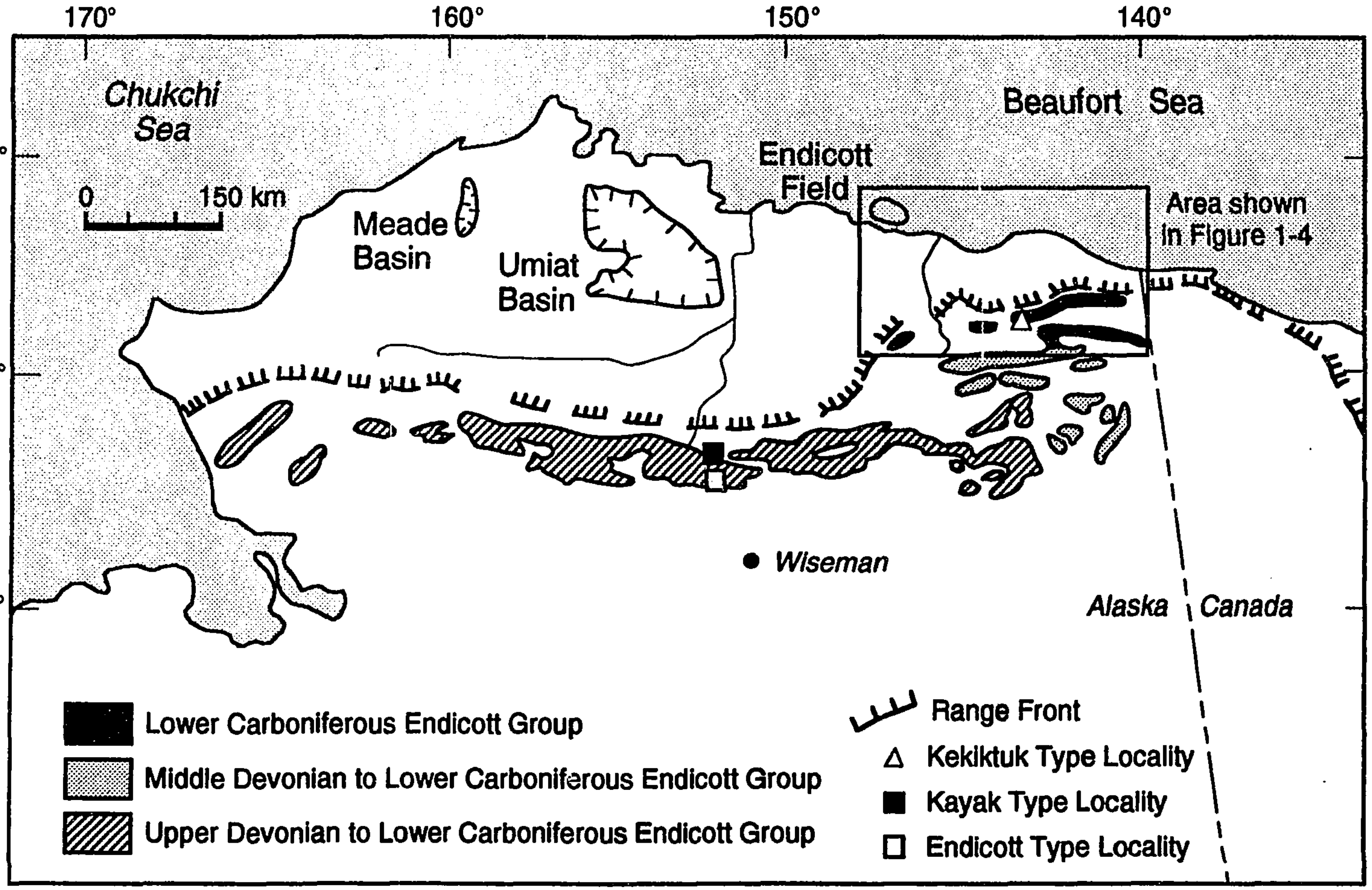

Figure 1-3 - Generalized outcrop of the Endicott Group in northern Alaska. Adapted from Anderson (1991), Moore and Nilsen (1984), and Reiser et al. (1980).

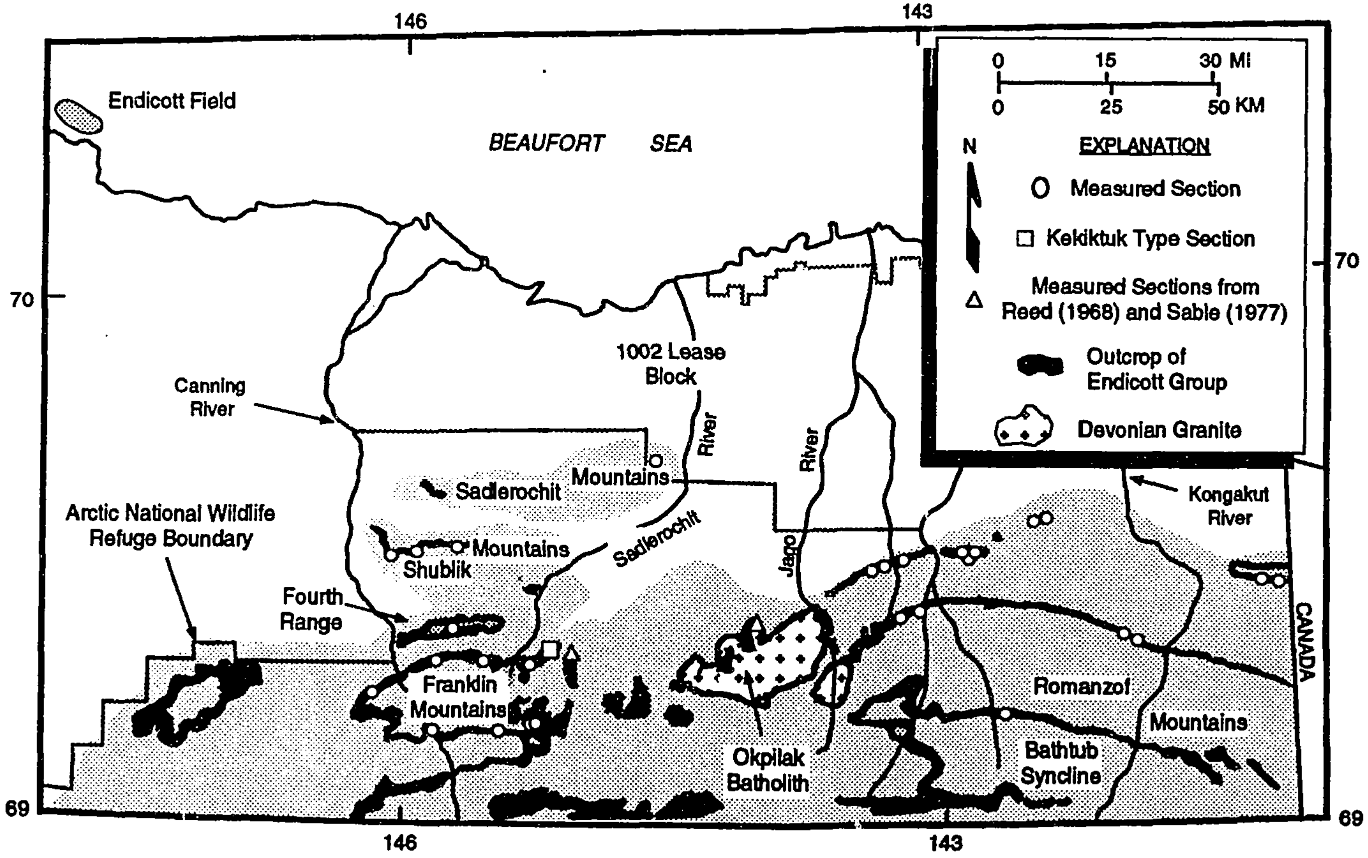

Figure 1-4 - Map of the northeastern Brooks Range showing the locations of measured sections. Modified from Bird et al. (1987).

Brooks Range that truncates rocks as young as Early Devonian (Blodgett et al., 1991) and represents a fundamental change from dominantly contractional deformation below to extensional deformation above (Moore et al., 1992). In the northeastern Brooks Range, the Carboniferous Endicott Group rests above this unconformity and consists, in ascending order, of fluvial and marginal-marine terrigenous clastic rocks of the Kekiktuk Conglomerate and marginal- to shallow-marine terrigenous clastic and carbonate rocks of the Kayak Shale (Figures 1-2 and 1-4). The Endicott Group is latest Tournaisian to Visean in age (Armstrong and Mamet, 1977; Utting, 1990, 1991a, 1991b), and forms the base of a northward-onlapping succession (Brosge et al., 1962; Nilsen, 1981) of terrigenous clastic and carbonate strata assigned to the Ellesmerian sequence (Figure 1-1).

In the Continental Divide region of the eastern Brooks Range (Figure 1-3), the Carboniferous Endicott Group is slightly older (Tournaisian to Visean) than corresponding rocks in the range-front region and is situated unconformably above a thick Middle to Upper (?) Devonian terrigenous clastic succession (Figure 1-5a; Anderson et al., 1992). The Devonian and Lower Carboniferous successions have been interpreted to record the rift and subsequent early drift phases, respectively, in the formation of a passive continental margin by Anderson and Wallace (1991) and Anderson et al. (1992). Farther south of the Continental Divide in the eastern Brooks Range, and throughout the central and western Brooks Range (Figure 1-3), a stack of south-derived allochthons contains Upper Devonian through Lower Cretaceous rocks (Mull, 1982; Moore et al., 1992). The structurally lowest allochthon, referred to as the Endicott Mountains allochthon (Mull, 1982), contains a thick Upper Devonian to Lower Carboniferous clastic wedge that consists of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale (Figure 1-5b; Moore et al., 1992). This wedge records south- and southwestward progradation of major fluvial-deltaic depocenters from the

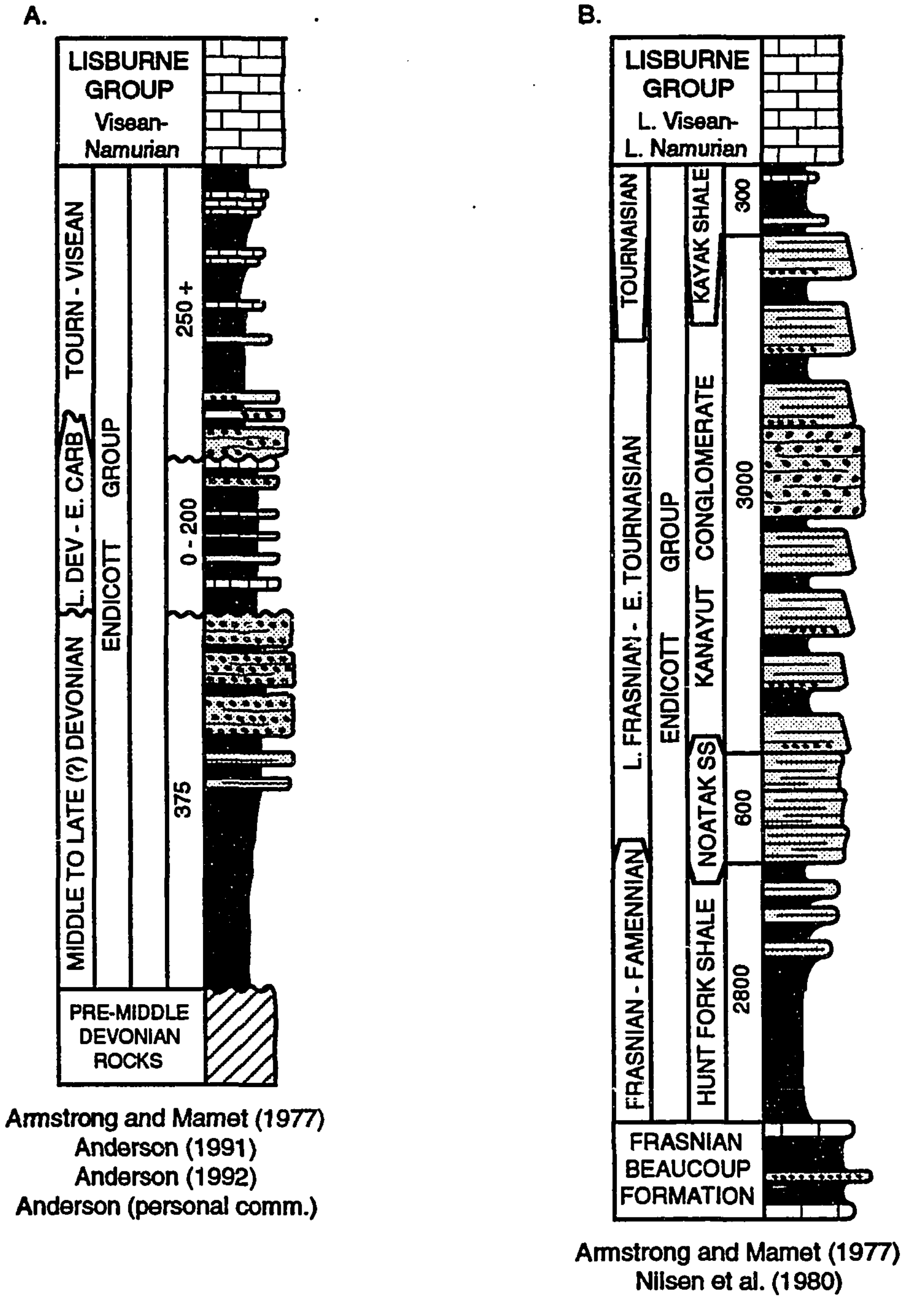

Figure 1-5 - Generalized columnar sections of the Endicott Group. A. Continental Divide region of eastern Brooks Range, B. southern, central, and western Brooks Range. Stratigraphic thicknesses in meters.

Late Devonian-Early Carboniferous basin margin (Moore and Nilsen, 1984; Moore et al., 1992). Middle and Upper Devonian terrigenous clastic rocks are missing in the northeastern Brooks Range.

These regional relations suggest that Middle Devonian to Lower Carboniferous strata in the Brooks Range are part of a southward-thickening and -deepening sedimentary wedge that was constructed during the rift and early drift phases in the evolution of a passive continental margin (Anderson and Wallace, 1991; Anderson et al., 1992; Moore et al., 1992). Further evidence of Devonian rifting is provided by common and widespread bimodal volcanic rocks interbedded within Devonian sedimentary rocks in the southern Brooks Range (Dillon et al., 1987; Dillon, 1989; Moore et al., 1992).

In the northeastern Brooks Range (Figures 1-3 and 1-4), the Kekiktuk Conglomerate is thickest (up to 128 m) where it fills incised paleovalleys and progressively thins toward, and eventually pinches out against, adjacent paleotopographic highs (LePain and Crowder, 1992b). These relationships indicate that where the Kekiktuk Conglomerate is thickest, fluvial systems were confined within incised paleovalleys cut into pre-Middle Devonian rocks and, where only a thin veneer of Kekiktuk is present, it is the record of deposition on the flanks of paleotopographic highs on the sub-Mississippian unconformity (chapter 2).

Slow post-rift subsidence of continental crust landward of the hinge zone (e.g. Braun and Beaumont, 1989), combined with eustatic sea-level rise throughout Early Carboniferous time (Hallam, 1984), resulted in regional transgression, flooding of fluvial dispersal systems, and establishment of a broad suite of marginal- and shallow-marine depositional environments recorded in the Kayak Shale (chapters 3 and 4). As transgression continued, estuarine conditions developed above valley-filling fluvial and marginal-marine successions of the

Kekiktuk Conglomerate (chapter 3). Local paleotopographic highs were onlapped and buried beneath a veneer of marginal-marine mud of the Kayak Shale.

The Kayak Shale onlaps and pinches out above a regional paleotopographic high in the Sadlerochit Mountains (Figure 1-4). The Sadlerochit high was transgressed and buried beneath shallow-water carbonate rocks of the Lisburne Group by late Visean time (zone 16i, earliest Chesterian; Armstrong, 1974). The Kayak Shale is absent and thin, and discontinuous successions of the Kekiktuk Conglomerate or rocks of the Lisburne Group rest non-conformably on the Devonian Okpilak batholith around its margins. These indicate that this feature also was a paleotopographic high throughout much of the Visean. Armstrong (1974) and Armstrong and Bird (1974) suggest the Sadlerochit high extends eastward, north of Leffingwell Ridge, to the Canadian border on the basis of foraminera biostratigraphy of the Lisburne Group. Along Leffingwell Ridge, the Kekiktuk Conglomerate is thin and discontinuous and the Kayak Shale is continuous and forms successions up to 285 m thick.

Paleogeographic reconstructions for Carboniferous strata in the northeastern Brooks Range show fluvial and marginal-marine sand of the Kekiktuk Conglomerate to the north and carbonate sediments of the Lisburne Group to the south (Armstrong, 1974; Armstrong and Bird, 1974). Between these areas, terrigenous mud and argillaceous carbonate sediment of the Kayak Shale accumulated under open- to restricted-marine conditions. These regional relations, combined with the limited thickness, widespread distribution, and stratigraphic position of the Kekiktuk Conglomerate below the marginal- and shallow-marine Kayak Shale, strongly suggest that the Carboniferous Endicott Group in the northeastern Brooks Range records deposition in a south-sloping upland area landward of the tectonic hinge zone of a subsiding passive continental margin. Subsidence, possibly combined with eustatic sea-level rise (e.g. Hallam, 1984), resulted in northward retreat of terrigenous clastic source areas, flooding of the low-relief rift-flank region, and ultimate establishment of an extensive shallow-water carbonate ramp (Lisburne Group).

In the northeastern Brooks Range, Cenozoic contractional deformation has resulted in several east-west trending anticlinoria (Wallace and Hanks, 1990). The Kayak Shale and associated strata crop out along the flanks of these anticlinoria (Figure 1-4).

LITERATURE REVIEW

The Endicott Group was originally named by Tailleur et al. (1967) for a thick regressive-transgressive succession of Upper Devonian through Lower Carboniferous clastic rocks that is present in the south-derived allochthons of the central Brooks Range (Figure 1-3) and that consists of the Hunt Fork Shale, Kanayut Conglomerate, and Kayak Shale. More recent literature on the Endicott Group in the central Brooks Range also includes a fourth formation named the Noatak Sandstone that is situated below the Kanayut Conglomerate (e.g. Moore and Nilsen, 1984). Even though their thickness and organization are distinctly different, Tailleur et al. (1967) considered the Kekiktuk Conglomerate and Kayak Shale in the northeastern Brooks Range to be stratigraphically equivalent to the type Endicott in the central Brooks Range and included the units in the original definition.

Brosge et al. (1962) named the Kekiktuk Conglomerate for a thin, discontinuous chert- and quartz-pebble conglomerate unit situated unconformably above pre-Middle Devonian rocks and below the Kayak Shale in the eastern Brooks Range. They noted that the unit was widespread in the area east of the Canning River and north of the Brooks Range divide, and designated a type section a few kilometers east of the Sadlerochit River (Figure 1-4). Reed (1968) and Sable (1977) mapped the areas around the type section and the Okpilak batholith, respectively, and interpreted the Kekiktuk to record deposition in a fluvial to marginal-marine setting.

Nilsen et al. (1980, 1981) provided the first detailed description of the organization and sedimentology of the Kekiktuk Conglomerate at its type section. They recognized three informal members, designated lower, middle, and upper. They interpreted both the lower and middle members as a record of deposition in a braided fluvial setting. They stated that the lower member was derived from local sources with a minimum amount of transportation to the depositional site, whereas, the middle member contained sediment derived from more distant sources. The upper member was interpreted to record deposition in a meandering fluvial system.

Woidneck et al. (1987), Melvin (1987, in press), and Miller (1991) have studied the Kekiktuk in the subsurface near Prudhoe Bay (Figures 1-3 and 1-4). At Endicott Field, a few kilometers northeast of Prudhoe Bay, the Kekiktuk is latest Tournaisian to early late Visean in age (Ravn, 1991). In the subsurface, the Kekiktuk is referred to as the Kekiktuk Formation, has been subdivided into three informal members, referred to as zones 1, 2, and 3, and is associated with syndepositional extensional basins. Major extensional faults strike west northwest-east southeast. Zone 1 is dominated by finer-grained lithologies, including mudstone, siltstone, fine-grained sandstone, and coal, and is interpreted to record deposition in swamp and associated low-energy terrestrial environments (Melvin, 1987). Zone 2 records deposition in sandy-bedload streams, and zone 3 records deposition in meandering fluvial systems and associated overbank environments (Melvin, in press).

Bloch et al. (1990) interpreted the Kekiktuk in the subsurface and in outcrop to record deposition in large fan-delta systems. In the 7 Sag Delta well west of the Sagavanirtok delta, they recognized two depositional sequences, a lower progradational sequence and an upper aggradational sequence, and noted that both are the "...products of a fan delta-lacustrine-swamp regime." In outcrop in the northeastern Brooks Range, they recognized nine depositional facies, including valley-fill, several varieties of braided stream and distributary channel-fills, beach-strand plain, and lacustrine-swamp, and noted the similarity between these facies and those recognized in the subsurface. They suggested that the facies distribution in surface and subsurface Kekiktuk successions was similar to that observed in the Van Horn Sandstone in Texas and the Fort Union and Wasatch Formations in the Powder River Basin, which have been interpreted as the products of wet alluvial fans.

Bowsher and Dutro (1957) named the Kayak Shale for ~290 m of Lower Carboniferous marine black and dark gray shale, siltstone, sandstone, and argillaceous limestone exposed in the central Brooks Range (Figure 1-3). At its type locality, the Kayak is Tournaisian in age (Armstrong and Mamet, 1977), and is situated disconformably above the Upper Devonian-Lower Carboniferous Kanayut Conglomerate and disconformably below the Lisburne Group. Bowsher and Dutro (1957) recognized five informal members in the Kayak Shale including, in ascending order, a basal sandstone, lower black shale, argillaceous limestone, upper black shale, and a red limestone. Brosge et al. (1962), while working on the Paleozoic sequence in the eastern Brooks Range, recognized a similar black shale succession below the Lisburne Group in exposures east of the Canning River. They considered it to be of Lower Carboniferous age, and referred to it as the Kayak (?) Shale. Following current stratigraphic terminology, we refer to this succession as the Kayak Shale.

A.K. Armstrong and B.L. Mamet have carried out detailed studies of the Carboniferous Lisburne Group throughout the Brooks Range and North Slope subsurface (Armstrong et al., 1970; Mamet and Armstrong, 1972; Armstrong and Mamet, 1975, 1977; Armstrong, 1974; Armstrong and Bird, 1974). Their measured sections usually begin in the uppermost beds of the Kayak Shale, and at a few locations, include the entire Endicott Group. Their work has provided biostratigraphic information for the uppermost beds of the Kayak Shale in the northeastern Brooks Range (Mamet's zones 11 through 14 - late Visean/late Meramec) and has clearly established the northward-onlapping relations for the Endicott and Lisburne Groups.

CHAPTER 2: TRANSGRESSIVE FLUVIAL SEDIMENTATION ON A PASSIVE CONTINENTAL MARGIN: DEPOSITION OF THE KEKIKTUK CONGLOMERATE

The diverse terrigenous clastic and carbonate rocks of the Ellesmerian sequence (Figure 2-1) in northern Alaska were deposited on a south-facing passive continental margin during Early Carboniferous to Early Cretaceous time (Bird and Molenaar, 1987). The base of the Ellesmerian sequence is composed of the Kekiktuk Conglomerate and Kayak Shale of the Endicott Group (Figure 2-2), a widespread transgressive succession whose regional distribution records increasing accommodation due to relative sea level rise. The Kekiktuk Conglomerate is a thin (0-128 m), fluvial to marginal-marine succession situated above a regional angular unconformity. This unconformity represents a hiatus of at least 35 Ma (DNAG time scale - Lower Devonian below and latest Tournaisian-earliest Visean above; Blodgett et al., 1991; Utting, 1990, 1991a, 1991b), and likely records the transition from dominantly contractional tectonics below to extensional tectonics above, followed by thermally controlled subsidence (Anderson and Wallace, 1991; Moore et al., 1992).

Stratigraphic cross-sections from passive continental margins typically show a wedge of sediment that thickens abruptly seaward of the tectonic hinge zone. This wedge develops during the post-rift or drift phase of passive continental margin evolution, when thinned continental crust cools and sinks in a process known as thermally controlled subsidence (Steckler and Watts, 1982). Most cross-sections that extend far enough in the landward direction show a transgressive succession that thins to a feather-edge some distance landward

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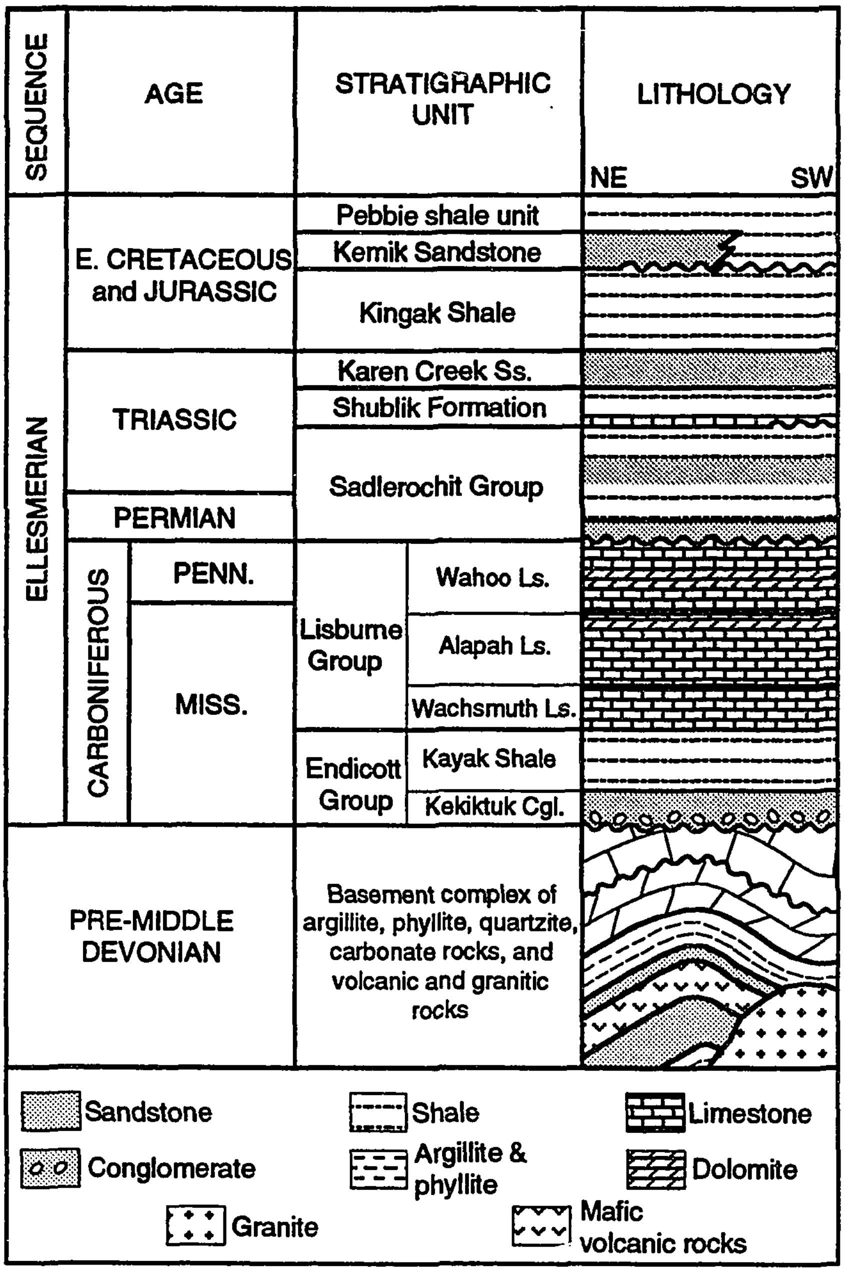


Figure 2-1 - Generalized column of the Ellesmerian sequence in the northeastern Brooks Range. No scale intended. Modified from Bader and Bird (1986).

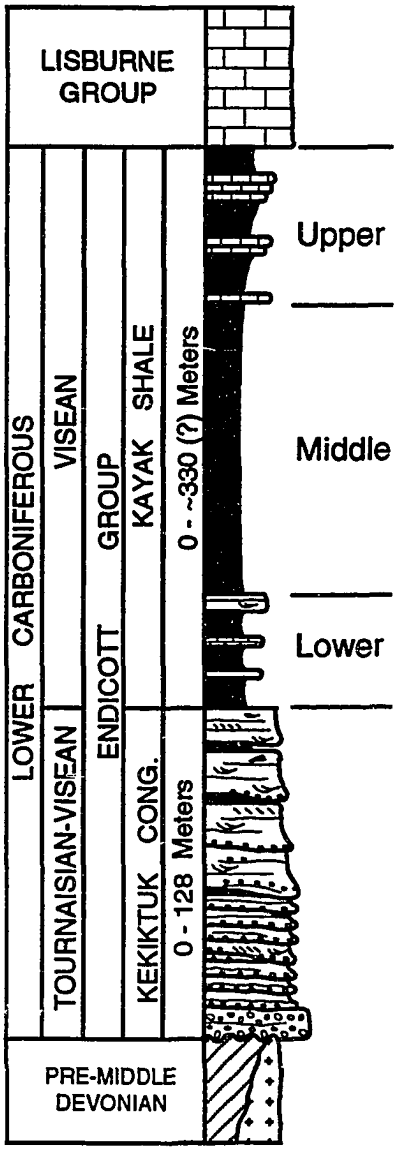


Figure 2-2 - Generalized column of the Endicott Group in the northeastern Brooks Range. No scale intended.

from the tectonic hinge zone (e.g. Dewey and Bird, 1970; Symonds et al., 1983). These landward thinning successions develop due to the flexural rigidity of unthinned continental crust landward of the tectonic hinge zone, where subsidence rates are lower than those associated with thinned continental crust seaward of the hinge zone (Steckler and Watts, 1982). Detailed examples of early post-rift successions deposited in this position are not common in literature on passive continental margins (e.g. Allen and Allen, 1990; Mitchell and Reading, 1986). The Carboniferous Endicott Group is a well-exposed example of a post-rift transgressive succession that was deposited landward of the tectonic hinge zone, over a rift-flank unconformity. The basal Kekiktuk Conglomerate also is an excellent example of a transgressive fluvial succession whose deposition was strongly influenced by relief on this unconformity. Thus, the tectonic setting played an important role in shaping the paleogeography and controlling deposition.

The coastal plain of the Arctic National Wildlife Refuge, to the north of the northeastern Brooks Range, is one of the most promising frontier areas for petroleum exploration in North America and coarse-grained rocks of the Kekiktuk Conglomerate may be present in its subsurface. Coeval fluvial successions are present in the subsurface to the northwest, have been assigned to the Kekiktuk Formation, and form an important reservoir rock at Endicott Field (1 to 6 km northeast of Prudhoe Bay). At Endicott Field, the Kekiktuk Formation contains an estimated one billion reservoir barrels of oil (Melvin, in press). The Kekiktuk Conglomerate, which is exposed in the northeastern Brooks, may provide invaluable information on the internal organization and paleogeographic distribution of equivalent strata in the subsurface to the north.

In this paper, we present a systematic description of the organization of the Kekiktuk Conglomerate in the northeastern Brooks Range and relate its organization to erosional relief on the sub-Mississippian unconformity and paleogeographic position landward of the tectonic hinge zone. Relief on this surface was the single most important control on accommodation space - after relative sea level rise - and the consequent distribution of Kekiktuk depositional environments and sediment dispersal patterns. We conclude with a reconstruction of the depositional setting that may serve as a predictive model for Kekiktuk deposition to the north of the northeastern Brooks Range, in the subsurface below the coastal plain in the Arctic National Wildlife Refuge.

REGIONAL GEOLOGIC SETTING

In the northeastern Brooks Range, the Endicott Group is a transgressive succession composed, in ascending order, of the fluvial to marginal-marine Kekiktuk Conglomerate, and the marginal- to shallow-marine Kayak Shale. The Kekiktuk Conglomerate is a thin, regionally extensive but discontinuous unit that is situated above a pronounced regional angular unconformity (Brosge et al., 1962), referred to herein as the sub-Mississippian unconformity (Figure 2-3). The sub-Mississippian unconformity truncates rocks as young as Early Devonian (Blodgett et al., 1991) and has been recognized across the North Slope subsurface and at widely spaced locations across the Brooks Range (Mayfield et al., 1988; Moore and Mull, 1989). The Kekiktuk Conglomerate is the basal terrigenous clastic phase of a northward onlapping (Armstrong 1974; Armstrong and Bird, 1974; Brosge et al., 1962; Nilsen, 1981) passive continental margin succession (Moore et al., 1992) assigned to the Ellesmerian sequence.

The depositional succession and relationships of the Endicott strata change significantly to the south and southwest, toward the Middle Devonian to Carboniferous basin margin. In the Continental Divide region of the eastern Brooks Range, the Carboniferous

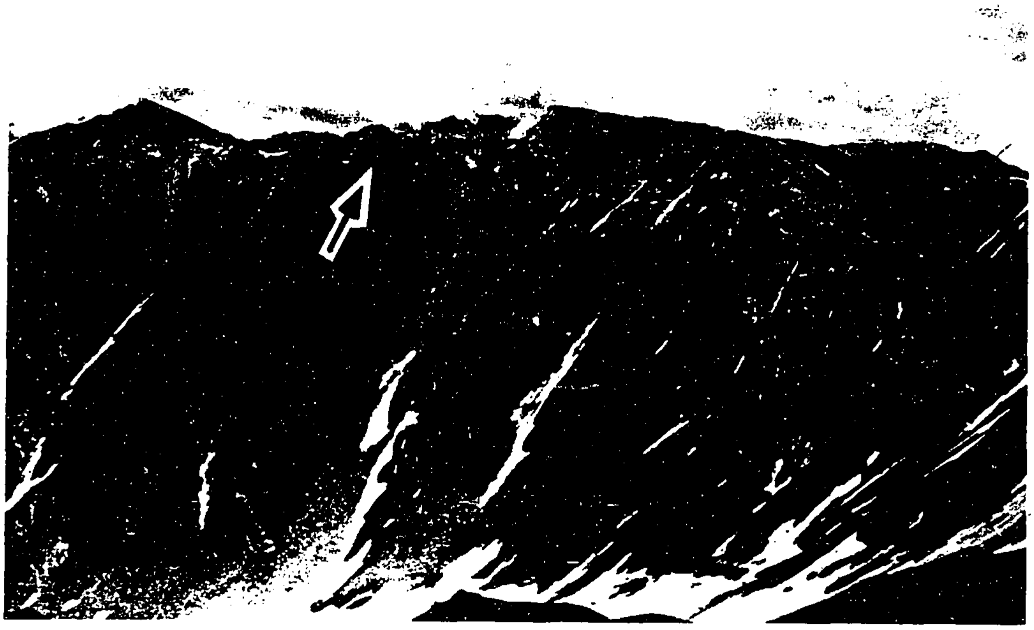


Figure 2-3 - Photograph showing sub-Mississippian unconformity in the northeastern Brooks Range. View looking toward the east in the northern Franklin Mountains. Note northward onlap relations visible in the Kekiktuk Conglomerate (see arrow). Approximately 75 to 80 m of strata is present above the unconformity.

Endicott Group is slightly older (Tournaisian to Visean; Anderson et al, 1992) than stratigraphically equivalent rocks exposed to the north, in the northeastern Brooks Range. In Divide region, the Carboniferous Endicott Group is situated unconformably above a thick Middle to Upper Devonian, dominantly terrigenous clastic succession that has been interpreted to record rifting by Anderson and Wallace (1991) and Anderson et al. (1992). This Middle to Upper Devonian succession is missing in the range front region, where Lower Carboniferous strata rest with angular discordance above pre-Middle Devonian rocks.

Farther south of the Continental Divide, in the eastern Brooks Range and throughout the central and western Brooks Range, a stack of south-derived allochthons contain Devonian through Lower Cretaceous, dominantly sedimentary rocks (Mull, 1982; Moore et al., 1992). Many workers believe these to be elements of a late Paleozoic to early Mesozoic, south-facing passive continental margin (Moore et al., 1992). The structurally lowest allochthon, referred to as the Endicott Mountains allochthon (Mull, 1982), contains a thick Upper Devonian to Lower Carboniferous succession of terrigenous clastic rocks that are assigned to the Endicott Group and are also not present in the northeastern Brooks Range. This succession is a thick transgressive-regressive-transgressive clastic wedge that records south and southwest progradation of major fluvial-deltaic depocenters that were situated along the Late Devonian-Early Carboniferous basin margin (Moore and Nilsen, 1984; Moore et al., 1992). The sub-Mississippian unconformity is absent in this succession - Devonian strata pass conformably upsection into Lower Carboniferous strata.

These regional relationships suggest that Middle Devonian to Lower Carboniferous strata in the Brooks Range are part of a southward-thickening and -deepening sedimentary wedge that was constructed during the rift and early drift phases in the evolution of a passive continental margin (Anderson and Wallace, 1991; Anderson et al., 1992; Moore et al., 1992).

Further evidence of Devonian rifting is provided by common and widespread bimodal volcanic rocks interbedded within Devonian sedimentary rocks along the southern Brooks Range (Dillon et al., 1987; Dillon, 1989; Moore et al., 1992).

These regional relationships combined with the limited thickness, widespread distribution, and stratigraphic position of the Kekiktuk Conglomerate below the marginal- and shallow-marine Kayak Shale strongly suggest it records deposition in an upland region (Moore et al., 1992) situated landward of the tectonic hinge zone along a subsiding passive continental margin. Relative sea level rise that initiated deposition of the Kekiktuk Conglomerate (and the Endicott Group) likely was partly the result of thermally controlled subsidence of the passive margin. Significant thermal subsidence of cooling thinned lithosphere seaward of a tectonic hinge zone is generally accompanied by slower, but regionally extensive subsidence landward of the hinge zone, perhaps reflecting higher flexural rigidity of the unthinned continental lithosphere (e.g. Allen and Allen, 1990; Braun and Beaumont, 1989; Scrutton, 1982; Steckler and Watts, 1982). Eustatic sea level rise from Late Devonian through late Early Carboniferous time (Hallam, 1984) also may have contributed.

In the northeastern Brooks Range, Cenozoic contractional deformation has resulted in formation of several east-west trending anticlinoria (Wallace and Hanks, 1990). The Kekiktuk Conglomerate crops out along the flanks of these anticlinoria (Figure 2-4).

Previous Studies of the Kekiktuk Conglomerate and Related Units

Brosge et al. (1962) named the Kekiktuk Conglomerate for a thin, discontinuous chert- and quartz-pebble conglomerate unit situated unconformably above pre-Middle Devonian rocks and below the Kayak Shale in the eastern Brooks Range. They noted that the unit was widespread in the area east of the Canning River and north of the Brooks Range divide, and

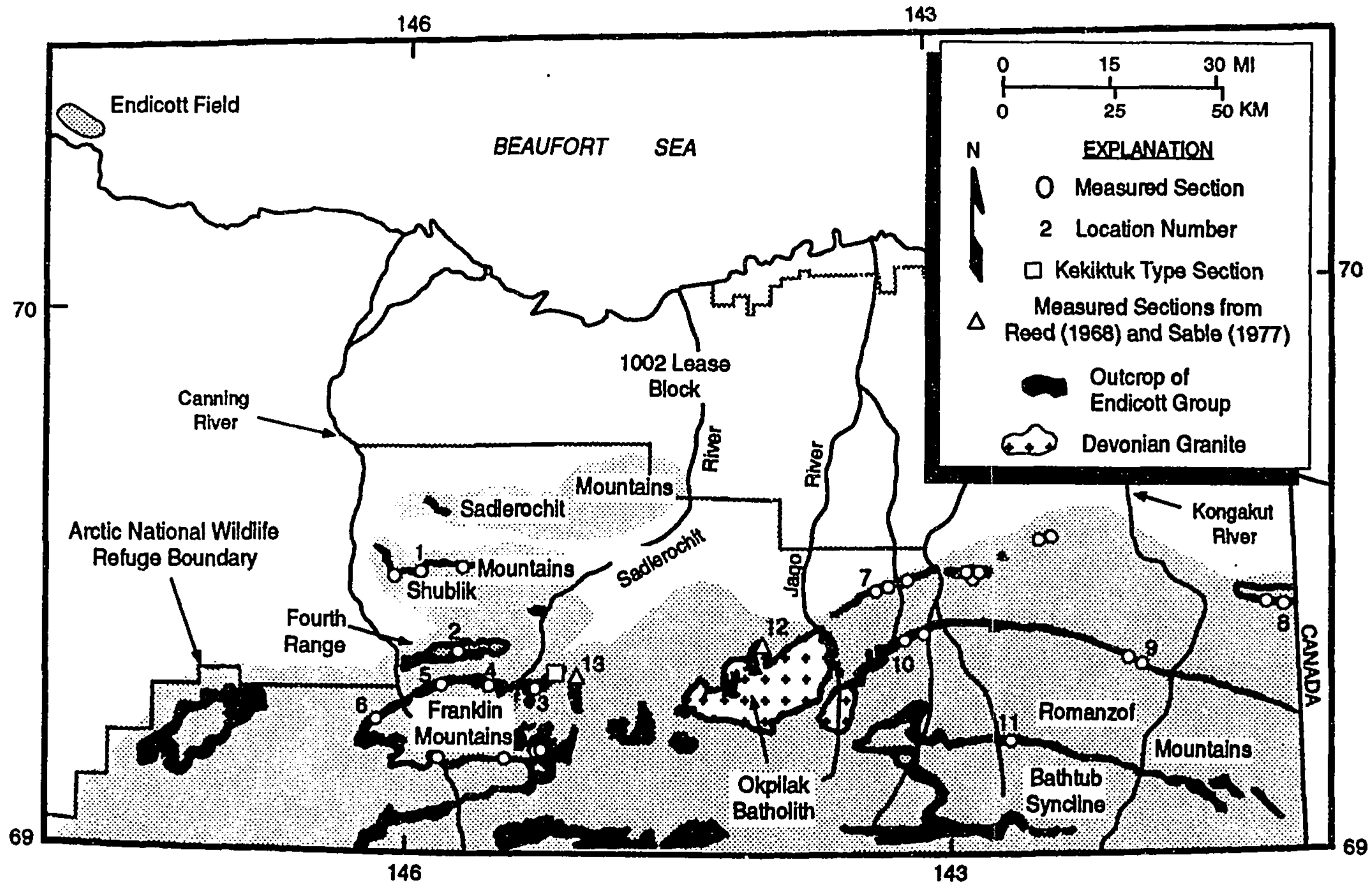


Figure 2-4 - Map of range-front region showing outcrop pattern for the Endicott Group. Locations referred to in chapter 2 are numbered. Modified from Bird et al. (1987).

designated a type section a few kilometers east of the Sadlerochit River (Figure 2-4). Reed (1968) and Sable (1977) mapped the areas around the type section and the Okpilak batholith, respectively, and interpreted the Kekiktuk to record deposition in a fluvial to marginal-marine setting.

Nilsen et al. (1980, 1981) provided the first detailed description of the organization and sedimentology of the Kekiktuk Conglomerate at its type section. They recognized three informal members, designated lower, middle, and upper. They interpreted both the lower and middle members as a record of deposition in a braided fluvial setting. They stated that the lower member was derived from local sources with a minimum amount of transportation to the depositional site, whereas, the middle member contained sediment derived from more distant sources. The upper member was interpreted to record deposition in a meandering fluvial system.

Woidneck et al. (1987), Melvin (1987, in press), and Miller (1991) have studied the Kekiktuk in the subsurface near Prudhoe Bay. At Endicott Field, a few kilometers northeast of Prudhoe Bay (Figure 2-4), the Kekiktuk is uppermost Toumaisian to early late Visean in age (Ravn, 1991). In the subsurface, the Kekiktuk is referred to as the Kekiktuk Formation, has been subdivided into three informal members, referred to as zones 1, 2, and 3, and is associated with syndepositional extensional basins. Major extensional faults trend west northwest-east southeast. Zone 1 is dominated by finer-grained lithologies, including mudstone, siltstone, fine-grained sandstone, and coal, and is interpreted to record deposition in swamp and associated low-energy terrestrial environments (Melvin, 1987). Zone 2 records deposition in sandy-bedload streams, and zone 3 records deposition in meandering fluvial systems and associated overbank environments (Melvin, in press).

Bloch et al. (1990) interpreted the Kekiktuk in the subsurface and in outcrop to record deposition in large fan-delta systems. In the 7 Sag Delta well west of the Sagavanirtok delta, they recognized two depositional sequences, a lower progradational sequence and an upper aggradational sequence, and noted that both are the "...products of a fan delta-lacustrine-swamp regime." In outcrop in the northeastern Brooks Range, they recognized nine depositional facies, including valley-fill, several varieties of braided stream and distributary channel-fills, beach-strand plain, and lacustrine-swamp and noted the similarity between these facies and those recognized in the subsurface. They suggested that the facies distribution in surface and subsurface Kekiktuk successions was similar to that observed in the Van Horn Sandstone in Texas and the Fort Union and Wasatch Formations in the Powder River Basin, which have been interpreted as the products of wet alluvial fans.

ORGANIZATION OF THE KEKIKTUK CONGLOMERATE

We have identified six depositional units in the Kekiktuk Conglomerate in the northeastern Brooks Range. The lithologic variability inherent in the Kekiktuk led to grouping closely related lithofacies into lithofacies associations. Each depositional unit recognized in this paper is essentially a multistory arrangement of one or two closely related lithofacies associations. Depositional units have been assigned letter designations and are referred to in abbreviated form as unit A, unit B, and so on. This approach was adopted to avoid an untenable number of individual lithofacies or lithofacies associations. In this section, descriptions and environmental interpretations are presented for each depositional unit. Lateral and vertical relationships between units are discussed in the following section. Descriptions, interpretations, and lateral and vertical relationships are summarized in Table 2-1.

Table 2-1 - Summary of depositional unit characteristics.

UNIT	TEXTURE	STRUCTURE	GEOMETRY
A	Unsorted to poorly sorted, clast- and rare matrix-sup. cobble- and pebble conglom.; minor poorly sorted, pebbly sandstone.	Thick- to very thick-bedded, unstrat. to crude horizontal strat., disorganized clast fabric; fining- and coarsening-upward trends.	Lenticular.
B	Poorly to moderately sorted, clast-sup. pebble conglom. and medium- to coarse-grained, pebbly sandstone.	Thin- to thick-bedded, unstrat. to horizontally stratified conglom. and sandstone; rare trough and planar cross-bedding; fining-upward couplets 0.4-1.5 m thick.	Sheet-like is most common, less commonly lenticular.
C	Moderately sorted, fine- to coarse-grained, sandstone and clast-sup. pebble conglom., minor organic-rich mudstone.	Multistory and multi-lateral fining-upward channel-fills from 1.0-3.4 m thick; thin- to thick-bedded; basal conglom., abruptly overlain by pebbly sandstone, abundant trough cross-bedding and common planar cross-bedding throughout channel-fills.	Broadly lenticular to sheet-like.
D	Moderately sorted, fine- to coarse-grained sandstone, common organic-rich mudstone, minor pebble-conglom. w/ minor mudstone intraclasts, minor coal.	Single story and multistory channel-fills from 1.0-4.0 m thick; similar to unit C, only w/ mudstone intraclasts in basal conglom. and planar cross-bedding is limited to top of channel-fills; mudstone successions up to 9.0 m thick cap most channel-fills, organic-rich, coal-bearing, w/ thin interbeds of sandstone.	Sheet-like?
E	Moderately to well-sorted, fine- to coarse-grained sandstone, minor to common pebble conglom, minor coal.	Thin- to thick-bedded multilateral and multistory channel-fills < 1.0 m thick; basal pebble conglom., abruptly overlain by sandstone and pebbly sandstone with common trough and planar cross-bedding, low-angle lamina and pebble conglom. stringers 1-2 clasts thick common near top of channel-fills.	Broadly lenticular and sheet-like.
F	Moderately to well-sorted, fine- to medium-grained sandstone, organic-rich mudstone, minor coal.	Thin- to medium-bedded, unstrat. to horizontally bedded and internally laminated, sandstone grades upward into interbedded, burrow-mottled sandstone, mudstone, and coal.	Sheet-like.

UNIT RELATIONS	INTERPRETATION
Unconform. overlies and onlaps pre-Middle Devonian rocks; sharp and grad. contact w/ unit B, C, or Kayak Shale.	Flood-generated, high sediment concentrat. flows, rare debris flows; local sed. sources, confined to incised valleys.
Sharp or grad. contact w/ unit A, or unconform. above pre-Middle Devonian rocks; onlaps pre-Middle Devonian rocks; grad. overlain by unit C.	Braid-bar complexes and shallow channel-fills in low-sinuosity, bedload-dominated fluvial system, confined to incised valleys.
Grad. lower contact w/ unit B, sharp lower contact w/ unit A,or unconform. above pre-Middle Devonian rocks; onlaps pre-Middle Devonian rocks; grad. contact w/ overlying unit E. Where unit E is absent, sharp contact w/ Kayak Shale.	Mixed-load, low-to moderate-sinuosity fluvial system, incised valley fill.
Unconform. w/ pre-Middle Devonian rock; grad. w/ overlying unit E. Where unit E is absent, sharp contact w/ Kayak Shale.	Mixed-load, moderate-to high-sinuosity fluvial system w/ adjacent perennial flood-basins, incised valley-fill.
Grad. lower contact with either unit C or D; contact relations w/ overlying Kayak Shale are uncertain - the contact appears to be abrupt based on three locations in the northern Franklin Mountains.	Mixed-load, low- to moderate-sinuosity and moderate- to high-sinuosity distributary channel-fills, distributary-mouth bars and/or adjacent beach-ridge deposits in marginal-marine setting, incised valley-fill.
Unconform. above pre-Middle Devonian rocks; grad. overlain by Kayak Shale.	Fluvial sheet flood and tidal flat/coastal swamp deposits above paleotopographic highs on sub-Mississippian unconformity.

We conclude with our depositional reconstruction for the Kekiktuk Conglomerate in the northeastern Brooks Range.

Depositional Unit A

Unit A is up to 36 m thick and consists of unsorted to poorly sorted, clast- and rare matrix-supported conglomerate and minor lenses of poorly sorted, pebbly, coarse-grained sandstone (Figure 2-5). Conglomerate beds are characterized by sharp, locally erosive lower contacts, massive texture or crude horizontal stratification, and disorganized clast fabric. Individual conglomerate beds range from 0.5 to 3.8 m thick and form lenticular lithosomes. Conglomerate beds near the base of unit A are commonly stained dark red-brown by iron oxides and commonly appear highly weathered. Conglomerate beds are usually amalgamated but locally are separated by pebbly sandstone lenses up to 0.4 m thick. Sandstones are characterized by their sharp bounding surfaces and their lack of internal stratification. Individual sandstone lenses have been traced laterally along local strike up to 15 m. Where exposure is good, unit A can be seen to onlap and pinch out against pre-Middle Devonian rocks over distances of several hundred meters.

Clasts are angular to sub-rounded and up to 45 cm in apparent diameter. The range of clast compositions reflects closely that of the immediately subjacent pre-Middle Devonian rocks. Vein quartz and chert predominate; however, quartz-semischist, quartz-wacke, quartzite, and phyllite are common clast varieties. Clasts are surrounded by a matrix of poorly sorted, fine- to coarse-grained lithic wacke and lithic arenite. Sand-sized grains are angular to sub-angular. Matrix is locally argillaceous and commonly contains angular pebbles and granules 'floating' within finer-grained material. Matrix-supported conglomerates contain abundant argillaceous material. Composition of sand- and silt-sized grains in matrix and in

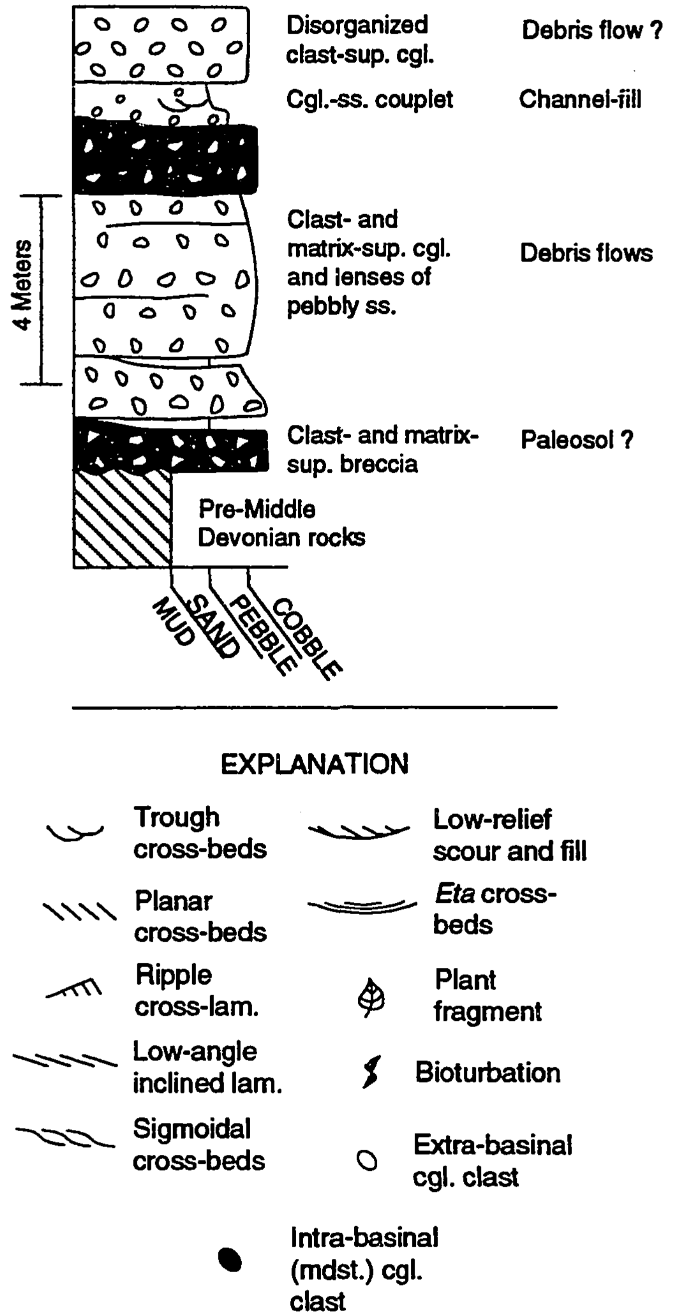


Figure 2-5 - Generalized column of depositional unit A and key to symbols used in Figures 5 through 10.

sandstone lenses is similar to that of the larger clasts; however, the sand- and silt-sized fraction is commonly enriched in chert and quartz.

Unit A records deposition under a variety of flow conditions including flood surges with associated sediment gravity flows, and traction currents. Clast-supported conglomerate of unit A probably resulted from subaqueous transport and deposition from turbulent fluidal flows with high sediment concentrations that were associated with flood surges similar to those outlined by Nemec and Steel (1984; fluidal flows in their terminology). Evidence for this interpretation includes characteristic disorganized clast fabric, lack of stratification or crudely developed horizontal stratification, and bimodal grain size distribution (pebbles with medium- to coarse-grained sandstone matrix; Collinson and Thompson, 1988). Rare matrix-supported conglomerates record deposition from cohesive debris flows, as suggested by their matrix-supported texture and the presence of abundant argillaceous material (Nemec and Steel, 1984). Sandstone lenses in unit A record deposition from traction currents during the waning phase of flood events (Rust, 1978). Discontinuous deposits of sand, similar to the sandstone lenses in unit A, are commonly observed on top of, and along the margins of, gravel deposits in modern coarse-grained fluvial systems that were deposited during the waning phase of high discharge events (Boothroyd, 1972; Rust, 1972, 1978). Highly weathered, iron-stained conglomerate beds near the base of unit A record localized preservation of basement-derived material with little or no subsequent transport, and are likely the record of paleosols. Nilsen (1981) arrived at a similar interpretation for highly weathered beds at the base of the Kekiktuk at its type locality.

Depositional Unit B

Unit B is up to 34 m thick and consists of couplets from 0.4 to 1.5 m thick of clast-supported pebble- to cobble-conglomerate and medium- to coarse-grained, pebbly sandstone (Figure 2-6). Unit B is distinguished from unit A by better organization, presence of upward-fining conglomerate-sandstone couplets, and greater textural maturity.

Conglomerate beds are up to 1.1 m thick and characterized by sharp, planar, erosive lower contacts, lack of stratification or crudely developed horizontal stratification, and disorganized to crudely developed imbricated clast fabric. Amalgamated conglomerate beds are present locally. Planar cross-bedding and low-angle inclined bedding have been observed, but are rare. Sandstone beds are up to 1.0 m thick and are characterized by sharp lower contacts with conglomerate. Although some beds are massive, a range of structures has been observed in sandstones of unit A, including well-developed horizontally stratified intervals up to 10 cm thick, sets and cosets of trough cross-beds, and rare sets of planar cross-beds. Conglomerate-sandstone couplets form sheet-like bodies that extend along local strike ~5 - >20 m, and are locally truncated by concave-upward scours overlain by thin (up to 1.5 m) fining-upward, channel-fill successions of pebble-conglomerate and pebbly sandstone. Rare dark gray-to-black organic-rich mudstone lenses up to 25 cm thick abruptly overlie coarser-grained lithologies. Mudstones usually contain poorly preserved plant fragments on bedding planes.

Vein quartz and chert are the dominant clast varieties. Quartzite, quartz-semischist, quartz-wacke, and phyllite are present locally but are not common components of the clast population. Clasts in conglomerates are surrounded by a sandstone matrix. Matrix and associated sandstones consist of pebbly, poorly to moderately sorted, medium- to coarse-grained lithic arenite and sublitharenite. Sand grains are angular to sub-rounded and the range

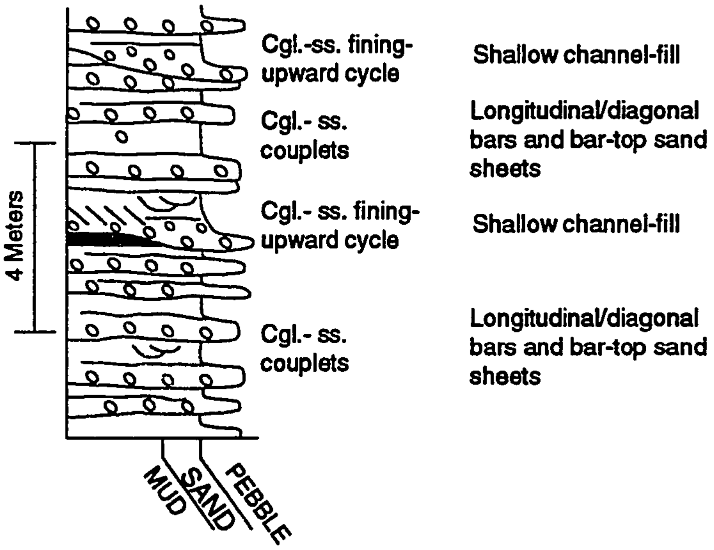


Figure 2-6 - Generalized column of depositional unit B.

of composition and compositional abundance is similar to that of larger clasts. Where unit B rests directly above pre-Middle Devonian rocks, clast composition in the basal conglomerate beds closely reflects the range of lithologies present in underlying rocks. At all locations, quartz and chert grains gradually increase in relative abundance up section.

Unit B records deposition within unstable, shallow, bedload-dominated, low-sinuosity fluvial systems. Conglomerate beds at the base of couplets record deposition during the early waning phase of flood events when flow competence became insufficient to transport gravel bedload. Unstratified to poorly stratified gravel deposits and conglomerate beds resembling those in unit B are commonly recognized features in modern and ancient low-sinuosity fluvial systems, and have been interpreted as the deposits of longitudinal and diagonal bars (Bluck, 1979; Miall, 1977; Smith, 1974; Rust,1972, 1978; Rust and Koster, 1984;) and bar complexes (Nilsen et al., 1980). The sandstone portions of couplets, dominated by a lack of internal stratification and crudely developed horizontal stratification, are interpreted as bar-top sand sheets deposited during the late waning phase of flood events. Rust (1972) recognized similar deposits in the Donjek River and interpreted them as the result of run-off as bars became emergent during the late waning phase of high discharge events. Concave-upward erosional scours and crudely defined fining-upward successions above them record deposition in shallow channels that flowed around and cut into large barforms. Shallow channels are characteristic features in modern low-sinuosity, bedload-dominated fluvial systems (Cant, 1982; Rust, 1972, 1978).

Depositional Unit C

Unit C is up to 40 m thick and consists of multistory fining-upward channel-fill sequences from 1.0 to 3.4 m thick (Figure 2-7). In addition to the vertical stacking of channel-

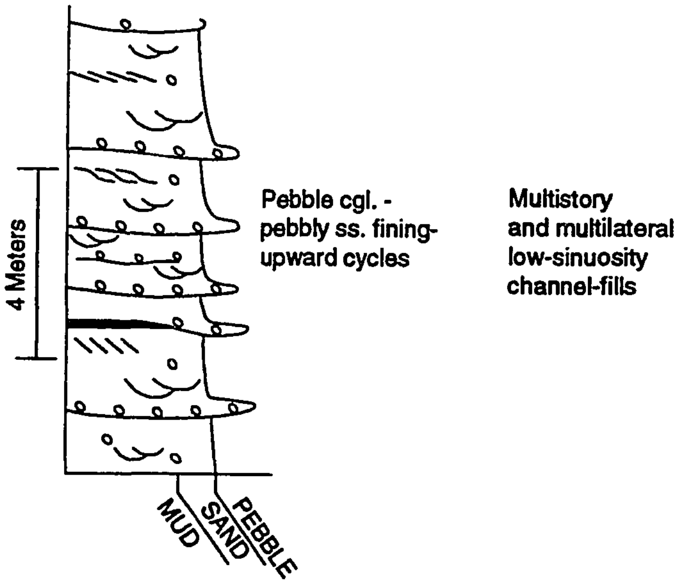


Figure 2-7 - Generalized column of depositional unit C.

fill sequences, individual sequences are commonly truncated laterally by erosional surfaces associated with other fining-upward channel-fills. Channel-fill successions consist, in ascending order, of clast-supported, granule- to pebble-conglomerate, moderately sorted medium- to coarse-grained pebbly sandstone, and minor organic-rich mudstone. Channel-fills invariably begin with conglomerate overlying a sharp, erosional surface. Conglomerate beds are up to 60 cm thick and characterized by a lack of internal stratification or only crudely developed horizontal stratification. At a few locations, horizontally stratified conglomerate grades laterally into trough cross-bedded conglomerate with sets up to 60 cm thick. Conglomerates commonly grade laterally into sandstone.

Sandstone beds range from 0.1 to 1.4 m in thickness and are characterized by sharp lower contacts (usually with conglomerate) and a variety of sedimentary structures. The most common structures include horizontal stratification up to 15 cm thick, sets and cosets of trough cross-beds with sets 0.1 to >1.0 m thick, and single sets of planar cross-beds <0.1 to 0.3 m thick. Scour and fill structures are common within sandstones and include low-angle planar cross-beds in sets up to 25 cm thick that overlie low-relief erosional surfaces, rare trough cross-beds with foresets that are concordant with the basal scour surface and resemble *eta* cross-beds of Allen (1963), and discontinuous conglomerate stringers 1 to 2 clasts thick that overlie irregular erosional surfaces. Log casts are present near the base of some sandstone beds. The scale of cross-bedding and stratal thickness decrease upward in individual channel-fill successions and the fining-upward trend is usually subtle (coarse to medium sand). Limited paleocurrent measurements indicate transport toward the south-southeast, south, and south-southwest.

Organic-rich mudstone in discontinuous lenses up to 30 cm thick caps some channel-fills. These mudstone lenses commonly contain plant fragments up to 25 cm long and log impressions up to 40 cm long. Mudstone lenses are usually truncated by overlying cycles.

Vein quartz and chert dominate the clast population in conglomerates of unit C, with rare quartz-semischist, quartz-wacke, quartzite, and phyllite. Sandstones in unit C consist of quartz arenite, with less than 5% chert and other rock fragments. Where unit C rests directly above pre-Middle Devonian rocks, sand and pebble composition within the basal few meters reflects lithologies present in nearby exposures of pre-Middle Devonian rocks. Conglomerates and sandstones become increasingly more quartzose upsection.

The multistory and multilateral organization, the coarse-grained nature of cycles, subtle fining-upward trends, complex organization of channel-fill sequences, and the low preserved mudstone content suggest that unit C records deposition in mobile, mixed-load fluvial channels. Cant (1982) noted that mixed-load, braided fluvial systems are characterized by greater topographic differentiation between in-channel and bar-top areas than bedload-dominated systems and produce vertical sequences with fining-upward trends. The features described for unit C are similar to those recognized in modern sandy braided streams by Cant and Walker (1978), Rust (1972), and Walker and Cant (1984) and in ancient braided stream successions by Allen (1983), Cant and Walker (1976), and Melvin (in press).

Conglomerates at the base of channel-fill sequences represent gravel lag deposits that were only transported during peak discharge periods, probably during flood events. Conglomeratic lag deposits are a commonly observed feature in many modern and ancient sandy fluvial systems and are widely interpreted to record transport only during peak discharge events (Allen, 1964; Cant and Walker, 1976, 1978; Walker and Cant, 1984). Trough cross-bedding is commonly observed in channel-fill sequences of unit C and records deposition from in-channel sinuous-crested dunes (Cant and Walker, 1978; Cant, 1982; Collinson and Thompson, 1988). The local presence of planar cross-beds in solitary sets suggests deposition from straight-crested sand waves (Collinson and Thompson, 1988) that migrated into deeper channel areas, and the cross-beds closely resemble structures described by Cant and Walker (1978) from the South Saskatchewan river. Rare horizontal bedding in the middle of some channel-fill sequences in unit C records localized development of upper flow regime conditions (Harms et al., 1982). Horizontal bedding near the top of some channel-fill sequences probably records vertical accretion associated with sand flats. Sand flats are common features in the modern South Saskatchewan river and typically near the top of channel-fill sequences (Cant and Walker, 1978).

Depositional Unit D

Unit D is up to 128 m thick and consists of multistory channel-fill sequences 1.0 to 4.0 m thick and mudstone successions up to 11.0 m thick (Figure 2-8). Individual cycles are laterally continuous at outcrop scale and begin with an erosional surface overlain by either pebble-conglomerate or pebbly, coarse-grained sandstone. Basal conglomerate/pebbly sandstone is sharply overlain by moderately sorted sandstone that fines progressively upsection from coarse to medium/fine grain sizes. The most striking feature of unit D is the thick, laterally continuous mudstone successions that cap many channel-fill sequences. Amalgamated channel-fill successions are present locally where intervening mudstones have been scoured away. Channel margins have not been observed.

Conglomerate and pebbly sandstone beds at the base of many channel-fill successions are up to 0.2 m thick. Overlying sandstone beds are 0.2 to 1.0 m thick. Sandstones of unit D exhibit a similar range of sedimentary structures as observed in unit C.

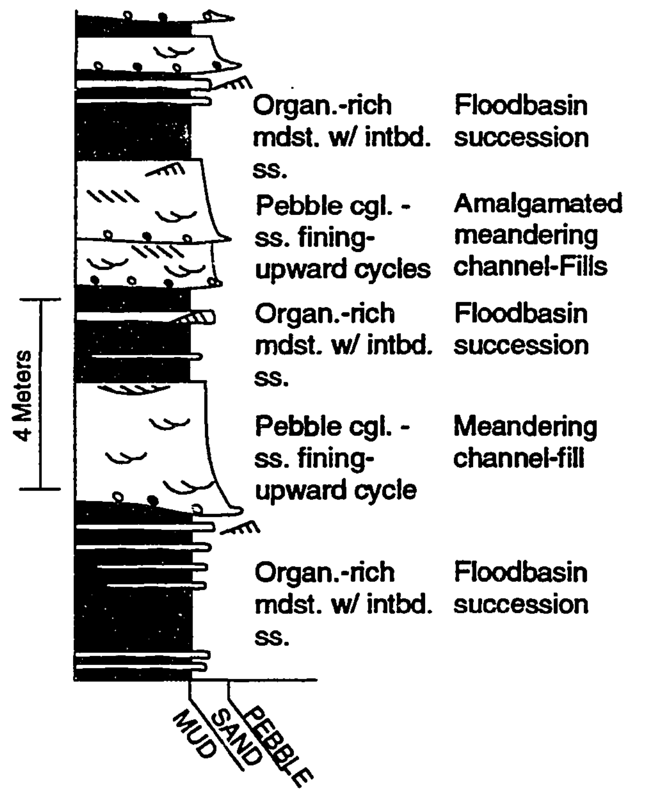


Figure 2-8 - Generalized column of depositional unit D.

However, trough cross-stratification is the dominant structure in the lower half of channel-fill successions in unit D and planar cross-lamination and straight-crested ripple bedforms are very common features in the uppermost beds. Also, scour and fill structures have been observed in sandstones of unit D, but are not as common as in unit C. Horizontally stratified sandstone with internally laminated beds up to 30 cm thick is common and grades laterally into trough cross-bedded sandstone. Near the top of unit D, the bases of some channel-fill successions exhibit pillow-like load structures that protrude downward into underlying mudstones.

The range of pebble and sand composition is similar to that observed in unit C, with the notable exception that mudstone intraclasts are usually a distinctive component of the clast population in conglomerates in unit D. Mudstone intraclasts make up <10% of the total clast population at any location. Sandstone beds are composed of quartz arenite and sub-litharenite (quartz + minor chert) and may locally contain chert and quartz pebbles and pebble-size mudstone intraclasts.

Mudstones may have sharp or gradational contacts with underlying sandstones and consist of dark green-gray to black, and locally, red-brown weathering organic-rich siltstone and silty shale. Mudstone intervals are up to 11 m thick, are laterally continuous at outcrop scale, and commonly contain variably preserved plant fragments and anthracitic coal lenses up to 30 cm thick. Branching, shaft-like structures oriented at high angles to bedding and filled with organic-rich mudstone and rarely coalified plant material have been observed and are probably plant root impressions. Laterally continuous sandstone beds and bedsets up to 30 cm thick are present in many mudstone intervals. Sandstones typically have sharp, locally erosive lower contacts with mudstone and rarely contain ripple cross-laminae 2 to 10 cm thick. Most sandstone beds are organized into bedsets with thin silty shale partings separating individual beds. Vertical and near-vertical burrows are present in some sandstone beds and are usually filled with dark gray or black, organic-rich siltstone. Sandstone commonly contains mudstone flakes up to 0.6 cm long. The upper few meters of many mudstone intervals form coarsening- and thickening-upwards successions defined by an increasing abundance of sandstone beds; successions are truncated above by sandstone of the next higher channel-fill.

Allen (1970) presented a facies sequence from the Devonian Old Red Sandstone in Britain and correlative rocks in the eastern U.S.A. that consists largely of trough cross-bedded sandstone with interbedded lenses of horizontally stratified sandstone. Sandstones in the sequence are situated above a thin conglomeratic lag developed above an erosional surface and are overlain by thick mudstone intervals. Allen interpreted this sequence to record deposition in a meandering fluvial channel and, more specifically, the sandstone component to record the deposits of point bars that accreted laterally toward active channels. Channel-fill and associated mudstone sequences in unit D are similar to Allen's facies sequence, and are interpreted to record deposition from high-sinuosity, mixed-load fluvial systems.

Conglomerate and pebbly sandstone at the base of channel-fill sequences record gravelly lags that were transported only during the peak discharge period in flood events. Basal lag deposits are a commonly observed feature in meandering rivers and represent the coarsest material available to the system that is only transported during peak discharge events (Cant, 1982; Walker and Cant, 1984). Mudstone intraclasts were derived from adjacent flood basins as flow eroded into cohesive bank material, and are also a commonly observed component of meandering systems (Collinson, 1986; Walker and Cant, 1984). Trough cross-bedded sandstone, which dominates the lower part of channel-fill sequences, records migration of sinuous-crested dunes (Collinson and Thompson, 1988) along the lower surface of point bars. Sinuous-crested dunes are usually present above basal lag deposits in channel-fill sequences from meandering systems and are commonly associated with point bar deposition (Allen, 1963, 1970; Harms et al., 1963). In fact, Collinson (1986) noted that dunes tend to be the dominant bedform on the lower parts of point bars. Horizontally bedded sandstone records deposition under upper flow regime conditions that developed locally on point bar surfaces. Horizontal stratification can occur at any level in point bar deposits (Collinson, 1986), and is a function of river stage and flow depth/velocity/grain size relationships required for plane-bed conditions to exist (Walker and Cant, 1984). Decreasing bed thickness and scale of cross-stratification toward the top of channel-fill sequences record gradually waning flow strength and deposition at successively higher positions on laterally accreting point bars (e.g. Allen, 1970).

Lateral accretion surfaces have not been recognized in unit D, possibly due to laterally discontinuous outcrops. Cant (1982) noted that the absence of lateral accretion surfaces is not a reliable indicator of a non-meandering system.

Mudstones in unit D record vertical accretion in flood basins that flanked active, high-sinuosity fluvial channels. Sandstone beds within mudstone successions record the episodic and abrupt input of coarser-grained material into the flood basin setting as crevasse splays breached channel margins. Crevasse splay deposits are commonly observed in flood basin settings associated with meandering systems (Collinson, 1986; Walker and Cant, 1984). The presence of coal lenses, common plant fragments, local rootlet horizons, and the dark gray to black color of mudstones suggest that flood basins were heavily vegetated and poorly drained (Collinson, 1986). These features combined with the absence of mudcracks and caliche deposits suggest a humid climate.

Depositional Unit E

Unit E is up to 10 m thick and consists of thin channelized successions < 1.0 m thick of pebble-conglomerate and coarse-grained sandstone, interbedded pebble-conglomerate stringers and laminated coarse-grained sandstone, and organic-rich mudstone (Figure 2-9). Unit E is overlain by marginal- and shallow-marine mudstone of the Kayak Shale. Channelized sequences begin with pebble conglomerate up to 20 cm thick overlying an irregular erosional surface. Conglomerate beds are characterized by their lack of lateral continuity at outcrop scale and usually cannot be traced laterally more than 15 m before pinching out above an erosional channel scour. Conglomerate is sharply overlain by coarse-grained, commonly pebbly, sandstone. Sandstones may be structureless or exhibit well-developed planar and trough cross-bedding in solitary sets; trough cross-beds are most common near the bases of channel-fill sandstones, while planar cross-beds are most common near the tops. Limited paleocurrent measurements from unit E indicate transport toward the southwest and northwest.

Low-angle inclined laminae and pebble conglomerate stringers 1 to 2 clasts thick occur near the top of some channel-fill sequences. Conglomerate stringers are laterally continuous in outcrop. Also, three-dimensional, symmetric megaripple bedforms usually cap the highest channel-fill sequence in unit E. Megaripples commonly have superimposed asymmetric current ripple bedforms. Lag deposits of pebble conglomerate are present in the troughs separating megaripples. Organic-rich mudstone beds have been observed separating channelized successions; mudstones range from 0 to 4 m thick and occur as laterally continuous (at outcrop scale) successions or as lenses truncated laterally by the next higher channel-fill sequence. Mudstones typically contain moderately to well-preserved plant fragments.

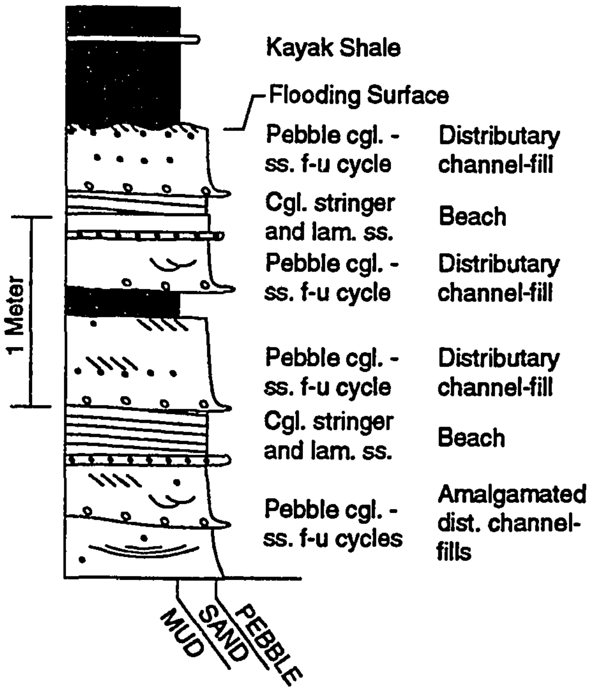


Figure 2-9 - Generalized column of depositional unit E.

Collectively, the association of thin, coarse-grained channel-fills, low-angle inclined laminae in coarse-grained sandstone, laterally continuous pebble conglomerate stringers, and plant fragment-bearing mudstones, and their position below marine mudstones of the Kayak Shale suggest deposition in a marginal-marine setting. The close association with marine mudstone of the Kayak Shale suggests that shallow channel-fill sequences in unit E record deposition in distributary channels (Elliot, 1986a). Trough and planar cross-bedding are commonly observed features in channel-fill sequences of unit E and record deposition from sinuous-crested dunes and straight-crested sandwaves, respectively (Collinson and Thompson, 1988). Channelized deposits in unit E resemble distributary channel-fills described by Kleinspehn et al. (1984) from Devonian fan-delta successions in Spitzbergen.

The position of low-angle inclined laminae and pebble conglomerate stringers near the tops of channel-fills suggests wave reworking and deposition in the surf zone, either as distributary-mouth bars that aggraded to sea level or as beach ridges that migrated laterally over distributary channel-fill sequences. Low-angle inclined lamination in marginal-marine deposits has been widely accepted as indicating deposition in the surf zone (Clifton, 1969; Elliot, 1986b; Heward, 1981; Reinson, 1984). Thin, laterally persistent pebble conglomerates resembling pebble conglomerate stringers in unit E have been described from high-energy beach and nearshore settings by Clifton (1973), DeCelles (1986), Leckie and Walker (1982), Leithold and Bourgeois (1984), and Massari and Parea (1988).

Depositional Unit F

Unit F is up to 20 m thick (usually <10 m) and consists of light gray, light tan-brown, and snow-white colored, horizontally stratified sandstone, with interbedded dark gray to black mudstone (Figure 2-10). Sandstones are internally laminated and typically consist of fine- to

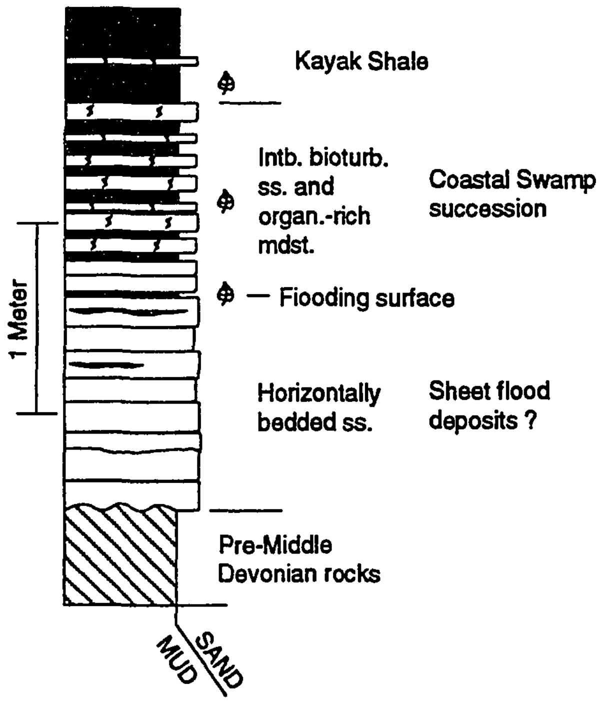


Figure 2-10 - Generalized column of depositional unit F.

medium-grained quartz arenite and sub-litharenite composed of quartz and chert. Minor phyllite, quartzite, quartz-wacke, and quartz-semischist grains are present in sandstone near the base of the unit. Mudstones are organic-rich and contain abundant, well-preserved plant fragments from 1.0 to 30.0 cm long, and minor anthracitic coal lenses up to 20 cm thick. A typical vertical sequence through unit F begins with 4 to 20 cm thick beds of horizontally stratified sandstone with minor mudstone flasers that pass upsection over a few tens of centimeters to a few meters into interbedded, burrow-mottled sandstone and organic-rich mudstone. Interbedded sandstone and mudstone pass upsection into organic-rich mudstone with lenticular laminae of fine-grained sandstone and minor coal lenses of the basal Kayak Shale.

Sandstones near the base of unit F record bedload transport in relatively low-energy coastal settings. Evidence of channelized flow has not been found, and horizontally bedded, internally laminated sandstones were probably deposited from sheet floods which spread across a low-relief peneplaned surface. Sheet flood deposits are associated with unconfined, sandy fluvial systems and consist of sequences dominated by parallel laminated sand (Cant, 1982; McKee et al., 1967). Interbedded sandstone and mudstone of unit F resembles the deposits of modern tidal flats and coastal swamps described by Elliot (1986b), Raaf and Boersma (1971), Reineck (1972), and Reineck and Singh (1980). In particular, Raaf and Boersma (1971) described several interbedded sand and mud successions from modern tidal flat settings in Europe that closely resemble interbedded sandstone and mudstone of unit F. They referred to these interbedded lithologies as their heterolithic facies and noted that they are commonly highly bioturbated. Interbedded organic-rich mudstone and burrow-mottled sandstone, abundant well-preserved plant fragments, and minor coal suggest deposition in a tidally influenced, low-energy marginal-marine setting that was situated seaward of unconfined, sandy fluvial systems.

DISTRIBUTION AND PALEOGEOGRAPHY OF DEPOSITIONAL UNITS

The Kekiktuk Conglomerate varies greatly in thickness and internal organization. This variability is reflected in outcrop throughout the northeastern Brooks Range by abrupt changes in thickness over short distances within individual depositional units, and by the paleogeographic distribution of units. In this section we describe facies relationships between depositional units, relate these to paleotopographic relief on the sub-Mississippian unconformity surface (see Figure 2-11 and Table 2-1 for summary), and discuss the paleogeography and climate of the northeastern Brooks Range during Early Carboniferous time.

Unit A is situated at the base of the Kekiktuk Conglomerate and is not widespread in the northeastern Brooks Range. It has been recognized at only a few locations in the northern Franklin Mountains and in the Romanzof Mountains, where it rests with angular discordance above pre-Middle Devonian rocks (Figure 2-11 and Locations 3 and 9 in Figure 2-12). Where exposures are good, unit A has been observed to onlap and eventually pinch out laterally against underlying rocks over short distances - as little as 400 m (Figures 2-13 and 2-14). These onlap relationships and the geographically restricted distribution suggest that unit A was confined to incised paleovalleys that were eroded into underlying pre-Middle Devonian rocks. Paleovalleys were probably on the order of 100's of meters to a few kilometers wide, 10's of meters to ~100 meters deep, and locally had steep enough side slopes to promote debris flows.

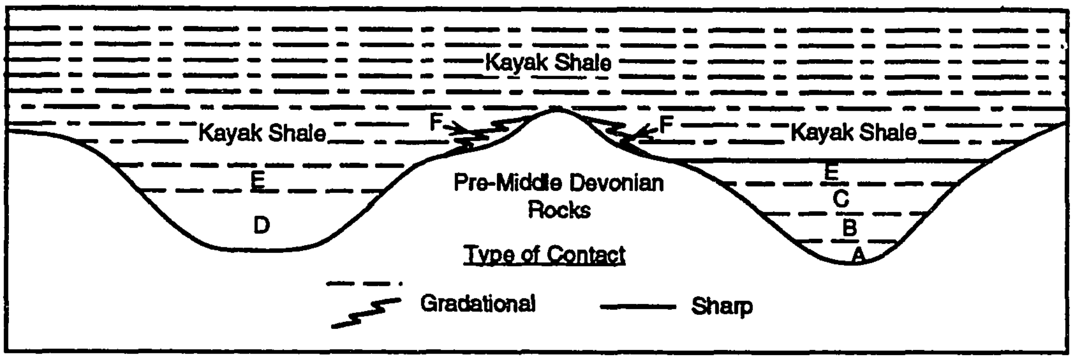
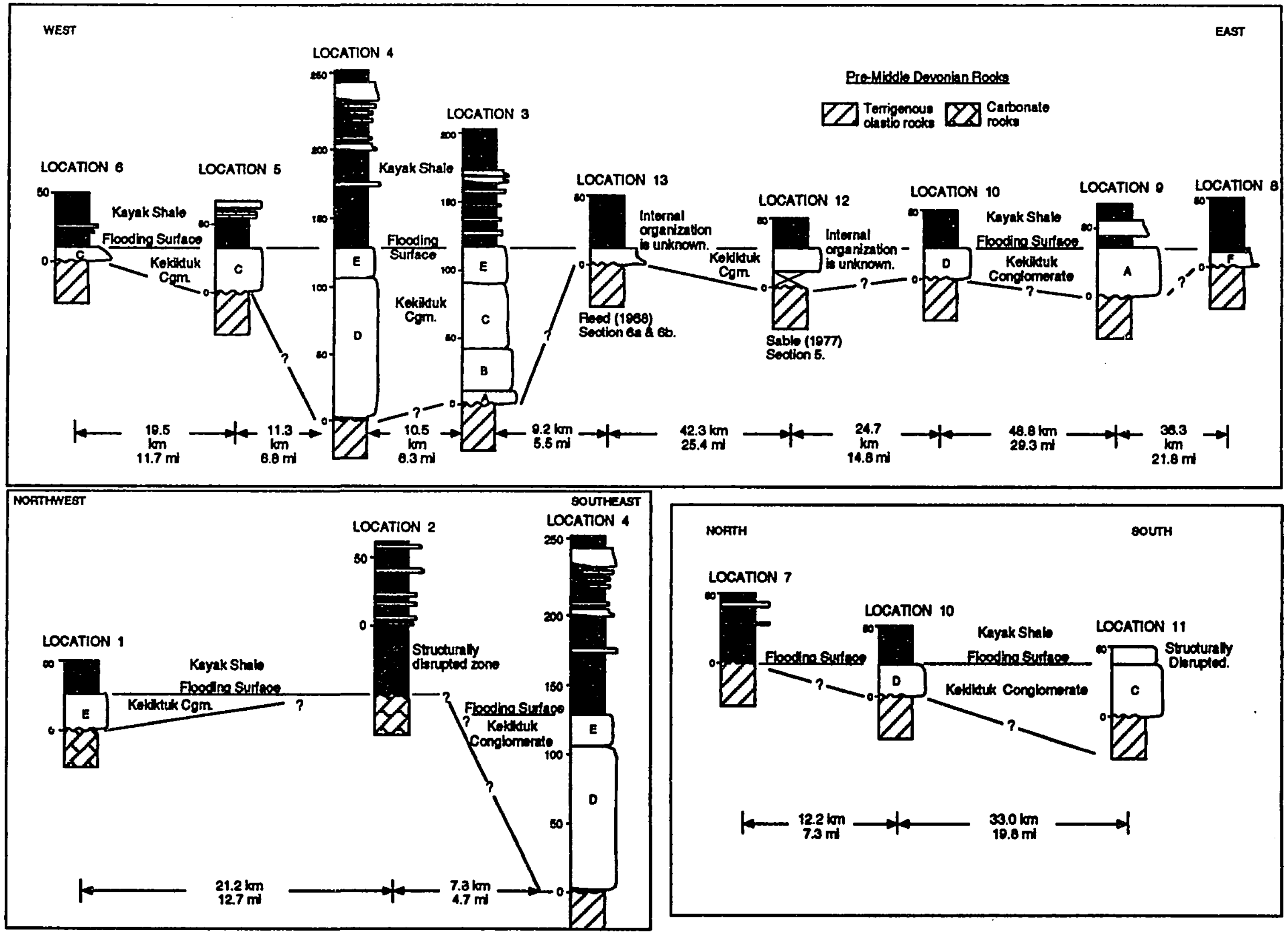


Figure 2-11 - Schematic cross-section through two paleovalleys showing the depositional geometry and relations between depositional units.

Figure 2-12 - Stratigraphic cross-section illustrating the regional distribution of depositional units in the Kekiktuk Conglomerate. The horizontal distance between sections is shown below each cross-section. Locations are shown in Figure 2-4. The datum used in correlations is the top surface of the Kekiktuk Conglomerate. The base of the Kekiktuk Conglomerate (and the sub-Mississippian unconformity) was correlated between locations using straight lines. Question marks were added between sections to indicate that interfluves may have separated adjacent sections - ie. adjacent sections may record deposition in separate valleys.


WEST
EAST
LOCATION 6
LOCATION 5
LOCATION 4
LOCATION 3
LOCATION 13
LOCATION 12
LOCATION 10
LOCATION 9
LOCATION 8
Pre-Middle Devonian Rocks
Terrigenous clastic rocks
Carbonate rocks
Kayak Shale
Flooding Surface
Kekiktuk Cgm.
Kekiktuk Conglomerate
Internal organization is unknown.
Reed (1968) Section 6a & 6b.
Sable (1977) Section 5.
19.5 km 11.7 mi
11.3 km 6.8 mi
10.5 km 6.3 mi
9.2 km 5.5 mi
42.3 km 25.4 mi
24.7 km 14.8 mi
48.8 km 29.3 mi
36.3 km 21.8 mi
NORTHWEST
SOUTHEAST
LOCATION 1
LOCATION 2
Structurally disrupted zone
21.2 km 12.7 mi
7.3 km 4.7 mi
NORTH
SOUTH
LOCATION 7
LOCATION 11
Structurally Disrupted.
12.2 km 7.3 mi
33.0 km 19.8 mi

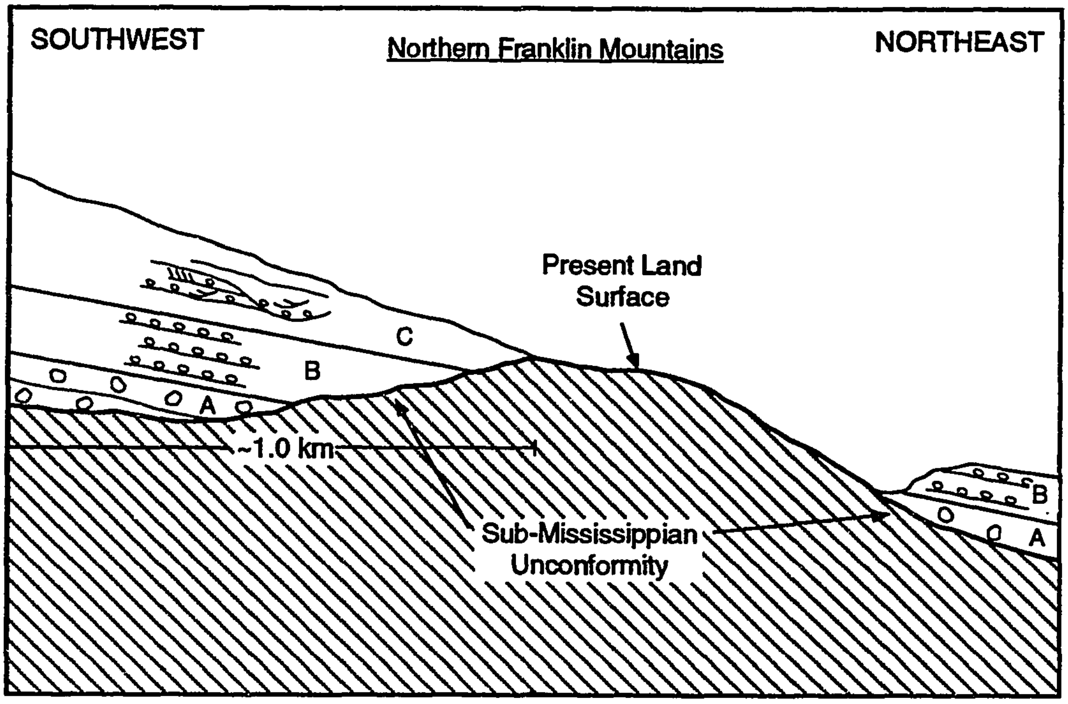


Figure 2-13 - Line drawing showing onlap relations between depositional units A, B, and C with pre-Middle Devonian rocks at Location 3 in the northern Franklin Mountains. Vertical scale is exaggerated.

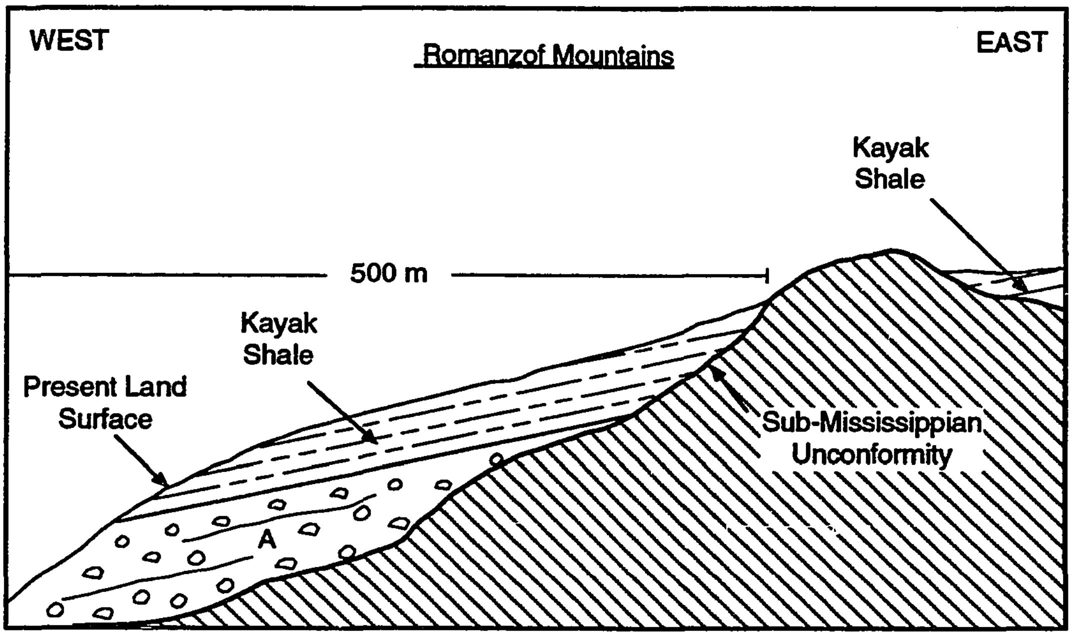


Figure 2-14 - Line drawing showing onlap relations between depositional unit A and the basal Kayak Shale with pre-Middle Devonian rocks at Location 9 in the Romanzof Mountains. Vertical scale is exaggerated.

Unit B has been recognized only in the northern Franklin Mountains, east of the Sadlerochit River, near the Kekiktuk type locality. In this area, unit B gradationally overlies unit A, where the latter is present. Where unit A is absent, unit B rests unconformably above pre-Middle Devonian rocks (Figures 2-11 and 2-12). At a few locations, unit B onlaps underlying rocks and, at one location (Location 3 on Figure 2-12), was observed to pinch out below the overlying unit C over a distance of 400 to 500 m (Figure 2-13). These observations suggest that unit B was also confined to incised paleovalleys that were probably on the order of hundreds of meters to a few kilometers wide, and up to 100 meters deep. The absence of debris flow deposits suggest that side slopes were relatively subdued.

Unit C has been recognized at a number of localities in the northeastern Brooks Range, including the Shublik, Franklin, and Romanzof Mountains and, therefore, is more widespread than either units A or B. A variety of basal contact relationships have been observed for unit C, including abrupt contact with unit A, gradational contact with unit B, and an unconformable contact above pre-Middle Devonian rocks where units A and B are absent (Figures 2-11 and 2-12). Unit C has been traced laterally at several localities and observed to onlap and thin above pre-middle Devonian rocks (Figure 2-13 and Location 3 on Figure 2-12). Onlap relationships suggest that unit C was also confined to incised valleys. The widespread distribution of unit C suggests that paleovalleys were probably on the order of a few kilometers to 10's of kilometers wide. As incised valleys were filled with alluvial sediment, valley bottoms gradually widened and side slopes were lowered. This is reflected in more widespread distribution of stratigraphically higher depositional units, such as unit C. The wider distribution of unit C may also indicate that fluvial systems were able to expand beyond the confines of paleovalleys onto south-facing alluvial plains.

Unit D has been recognized at only two locations in the northeastern Brooks Range, where it rests with distinct angular discordance above pre-Middle Devonian rocks (Figure 2-11 and Locations 4 and 10 on Figure 2-12). We have not been able to trace unit D laterally and, thus, an onlap relationship with underlying pre-Middle Devonian rocks has not been observed directly. The one location in the northern Franklin Mountains where unit D was recognized (Location 4 on Figure 2-12) contains a 128 m thick succession and constitutes the thickest Kekiktuk section measured in the northeastern Brooks Range, let alone the thickest example of unit D. Based on unit D's considerable thickness, we suggest that it was also confined to incised valleys.

Unit E has been recognized at a number of localities in the northeastern Brooks Range, including the Shublik, Franklin, and Romanzof Mountains, where it rests gradationally above either unit C or D or unconformably above pre-Middle Devonian rocks (Figures 2-11 and 2-12). In sand-rich Kekiktuk successions (Locations 3, 5, and 6 on Figure 2-12), the contact between unit E and the Kayak Shale is sharp. Whereas, in mud-rich Kekiktuk successions the contact is typically poorly exposed, but appears gradational at Location 4 and sharp at Location 10 (Figure 2-12). Where unit E is absent, units C and D are abruptly overlain by the Kayak Shale. This suggests that the contact between the Kayak Shale and the underlying depositional unit in the Kekiktuk is generally sharp and represents a marine flooding surface. Onlap relationships between unit E and underlying pre-Middle Devonian rocks have not been observed. However, unit E has only been recognized above relatively thick successions of the Kekiktuk Conglomerate, which suggests it was confined to broad, nearly filled paleovalleys.

Unit F has been recognized at a number of localities across the northeastern Brooks Range, where it consistently rests unconformably above pre-Middle Devonian rocks and is gradationally overlain by marginal- and shallow-marine mudstones of the Kayak Shale (Figures 2-11 and 2-12). Due to its low stratigraphic thickness and position below thick marine mudstone and ramp-carbonate successions of the Kayak Shale and Lisburne Group, respectively, unit F is typically poorly exposed and is probably much more widespread than recognized. Horizontally bedded and laminated sandstones that dominate the lower few meters of unit F indicate flow was unconfined by bedrock topography. We interpret unit F to record deposition above paleotopographically high areas on the sub-Mississippian unconformity, as a thin transgressive veneer that developed in a narrow marginal-marine belt. The gradational contact of unit F with the overlying Kayak Shale makes recognition of a marine flooding surface difficult. However, we place the flooding surface at the base of the first laterally continuous shale bed.

To sum up these observations, during latest Tournaisian-earliest Visean time the northeastern Brooks Range was characterized by gently rolling topography. Local fluvial incision cut valleys into underlying pre-Middle Devonian rocks. Local topographic relief from valley bottoms to adjacent interfluve areas ranged from 10's of meters upwards to ~128 meters, based on preserved thickness of the Kekiktuk. Paleovalleys were gradually infilled throughout Kekiktuk time and, at any given time during deposition, paleovalleys and associated topography were progressively buried as the coastline was approached. Limited paleocurrent measurements indicate transport generally toward the southeast, south, and southwest (Nilsen et al., 1981), but north-, east-, and west-directed transport is indicated locally (LePain, unpublished field notes). Although the regional paleoslope was toward the south and southwest (Nilsen et al, 1980, 1981), variability in paleocurrent direction is consistent with deposition in an upland region. As the valley systems were gradually filled with fluvial detritus, valley walls were progressively onlapped, and only a thin veneer of fluvial and marginal-marine sediment was deposited above paleotopographic highs - the interfluves separating paleovalleys. The present day coastal plain in the Arctic National Wildlife Refuge, north of the study area, and the coastal region in Delaware at the onset of the Holocene transgression (Kraft, 1971; Kraft and John, 1979) serve as close modern analogs to Early Carboniferous paleotopography in the northeastern Brooks Range.

Paleovalleys were generally vegetated, but to varying degrees (cf. thick mudstone successions with common coal of unit D with the others), and interfluve regions were probably devoid of vegetation. Schumm (1968) observed that from Devonian to early Mesozoic time, significant sediment stabilizing vegetation was limited to nearshore coastal plain regions and humid alluvial valleys, and that interfluve areas were characterized by their lack of runoff-retaining and sediment-stabilizing vegetation. The lack of vegetation in interfluve regions is supported by the absence of organic-rich mudstone (or any mudstone) and plant fragments in the basal beds of unit F. Additional support comes from the character of depositional units B and C which, with their low mudstone content and complex internal structure, suggest that these fluvial systems were prone toward flashy discharge events. Abrupt variations in river discharge are commonly associated with poorly vegetated areas (Schumm, 1968).

The climate during latest Tournaisian to Visean time was probably humid, as indicated by the plant spore assemblage recovered from the Kekiktuk Conglomerate and overlying Kayak Shale in the northeastern Brooks Range (Utting, 1990, 1991a, 1991b). The character of mudstones (i.e. dark gray to black color indicating deposition in dysaerobic to anaerobic, perennial flood basins or, at least, perennially saturated flood basins) and common coal lenses within the Kekiktuk Conglomerate support this view. Based on analysis of the land-plant spore assemblage from the Kekiktuk Formation in the subsurface at Endicott Field, and comparison with palynofloras from similar-aged rocks in Spitzbergen, Ravn (1991, 1992) concluded that northern Alaska was probably close to Spitzbergen during Early Carboniferous time and was situated at a subtropical to tropical latitude. He also noted the strong similarity between the Kekiktuk Formation in the subsurface and Late Carboniferous coal measures sequences in central North America and Europe, and observed that the latter are often cited as evidence for a tropical to subtropical climate (Ravn, 1991, 1992). Equatorial coal measures sequences were well developed in the Carboniferous (Witzke and Heckel, 1988).

This study yielded no evidence to indicate whether syn-depositional extensional faulting exerted any control over the distribution of depositional units. Melvin (in press), Miller (1991), and Woidneck et al. (1987) have demonstrated conclusively that extensional faults were active during deposition of the Kekiktuk Formation in the subsurface to the northwest, and that they were of primary importance in controlling the distribution and character of depositional environments. Outcrop discontinuity combined with a difference in trend between extensional structures in the subsurface and later contractional structures in the northeastern Brooks Range preclude detailed reconstructions of depositional geometry and trends. Evidence for extensional structures could easily be masked by later deformation (e.g. Mitchell and Reading, 1986). If there was syn-depositional extension during Kekiktuk deposition, it was minor based on the low maximum thickness (128 m) in outcrop.

Pre-Middle Devonian rocks were an important control on the development of paleotopographic relief on the sub-Mississippian unconformity and subsequent distribution of depositional units. For example, in the central Romanzof Mountains, unit A was deposited above and onlapped relatively non-resistant schistose and phyllitic sandstones (Location 9 on Figure 12). In this area, unit A eventually pinches out against more resistant bedded chert (Figure 14). We have documented other similar examples in the northeastern Brooks Range, where paleovalleys overlie relatively non-resistant pre-Middle Devonian rock types and valley-filling depositional units of the Kekiktùk onlap and pinch out laterlally over paleohighs in more resistant pre-Middle Devonian units.

DEPOSITIONAL RECONSTRUCTION

Deposition of the Kekiktuk Conglomerate began in the northeastern Brooks Range by latest Tournaisian-earliest Visean time, as indicated by palynomorphs from the base of the Kekiktuk along the southern margin of the study area (Utting, 1991b). Prior to this, fluvial incision and erosion characterized the region and little, if any, *preservable* sediment accumulated. Limited paleocurrent data from the Kekiktuk Conglomerate show considerable variability, but indicate transport mainly toward the west, southwest, and south (LePain, unpublished field notes; Nilsen et al, 1981). To the southwest, clast size trends and paleocurrent data from the thick, Upper Devonian to Lower Carboniferous Kanayut Conglomerate consistently indicate sediment transport toward the southwest (Nilsen et al., 1981). These observations suggest that sediment derived from erosion of uplifted pre-Middle Devonian rocks in the northeastern Brooks Range was probably flushed out of the region toward the south and southwest and incorporated into the Middle Devonian to Lower Carboniferous clastic wedge that developed along the south-facing basin margin of Arctic Alaska. Anderson and Wallace (1991) and Nilsen et al. (1980, 1981) arrived at a similar conclusion.

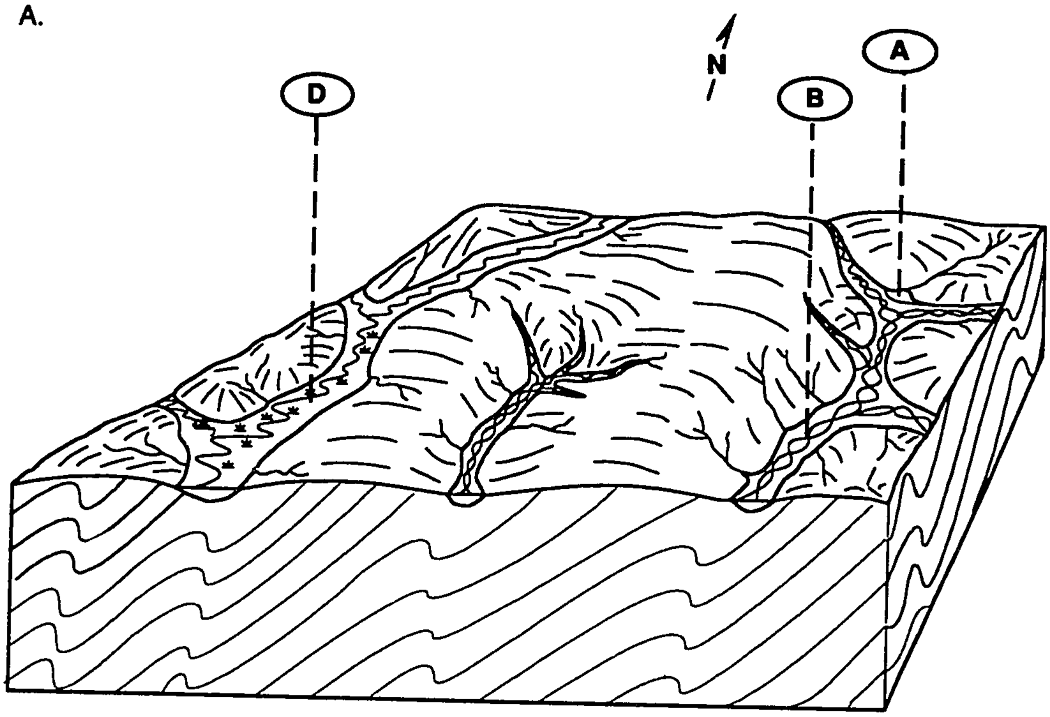
Beginning in latest Toumaisian-earliest Visean time, accommodation increased and fluvial deposition began in incised paleovalleys. Increased accommodation resulted from an upward and landward shift in stream equilibrium profiles. This change in base level was due to the combined result of onset of subsidence landward of the hinge zone during the thermally controlled subsidence phase of the evolution of the passive continental margin and of eustatic sea level rise. Cross-sections from passive continental margins generally include a thin post-rift transgressive succession that thins to a feather edge in a landward direction from the tectonic hinge zone (e.g. Dewey and Bird, 1970; Symonds et al., 1983), and are attributed to thermally controlled subsidence (Steckler and Watts, 1982).

Sediment initially consisted of texturally immature material from adjacent interfluve areas that was deposited from sediment gravity flows and high sediment-concentration flows (unit A), and from traction currents during the waning phase of flood events (unit B) in shallow, low-sinuosity, bedload-dominated channels (Figure 2-15a). Small alluvial fans may have been present locally at the base of steep slopes along valley margins. In other valleys or in different parts of the same valleys, where stream gradients were lower and valley widths greater, sediment consisted of a wide range of grain sizes, including pebble- to clay-sized particles that were deposited in high-sinuosity, mixed-load channels (unit D Figure 2-15a). Continued relative sea level rise resulted in gradual infilling of incised valleys and onlap over pre-Middle Devonian rocks. Units A and B filled narrow, incised paleovalleys that had relatively high valley bottom gradients. Unit D filled broad paleovalleys that had relatively low valley bottom gradients.

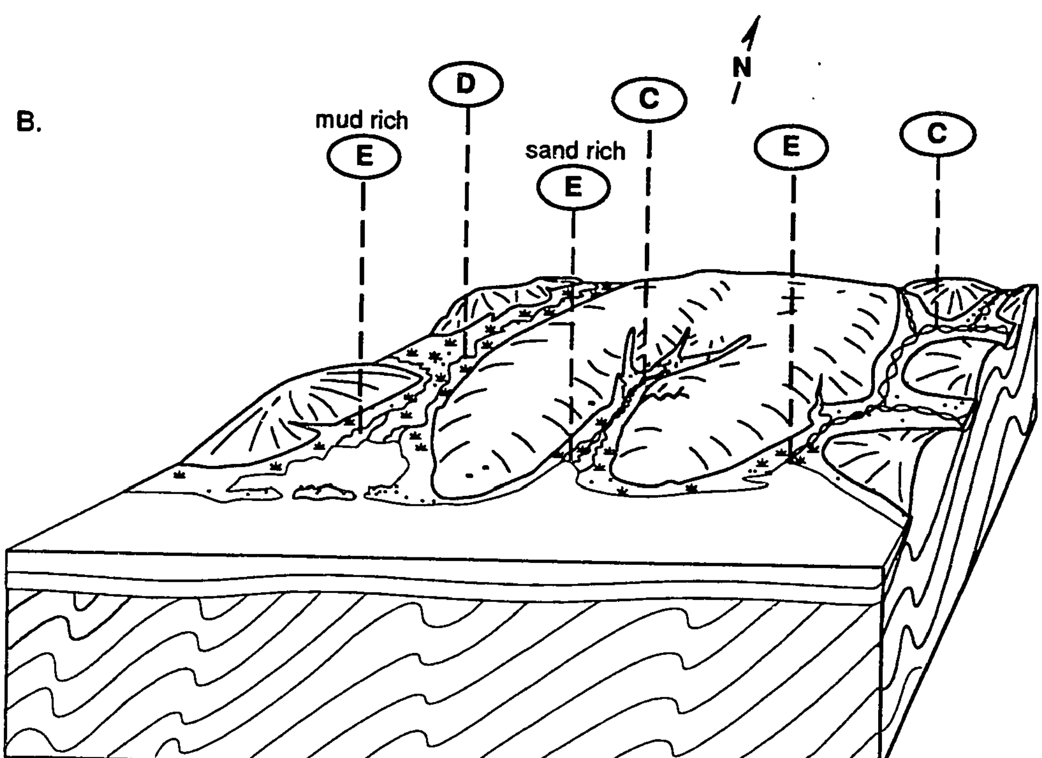
Gradual infilling of narrow, incised valleys by units A and B gave way to fluvial deposition on a more widespread scale in broad paleovalleys as recorded in unit C (Figure 2-15b). Valley widths were probably on the same scale as those suggested by unit D (Figures 2-15a and 2-15b). The lateral relationship of units A, B, and C to unit D is unknown. Based on its depositional character, unit D represents deposition where stream gradients were lower in different valley systems or parts of the same valley systems. A variety of fluvial styles existed, including the bedload-dominated, low- to moderate-sinuosity streams of unit C and the mixed-load, high-sinuosity systems of unit D. The mudstone content of unit D strongly suggests that

Figure 2-15 - Depositional reconstruction for the Kekiktuk Conglomerate. A. Depositional units A, B, and D. B. Depositional units C, D, and E and fluvial-to-marine transition. Note coastline is portrayed as non-deltaic.

A.



B.



flood basins were a prominent feature of the depositional landscape in the vicinity of mixed-load streams. As relative sea level continued to rise, coastal estuaries gradually encroached on the southern parts of paleovalleys, while northward onlapping fluvial systems continued filling valleys north of the strand line (Figure 2-15b).

A complex strand line defined the southern limit of alluvial systems and bedrock highs as recorded in depositional units E and F and the basal Kayak Shale (Figure 2-15b). Sand-rich shore-zone successions of unit E developed above thick valley-fill sequences where unit C was present, while mixed sand-mud shore-zone successions of unit E developed where unit D was present (Figure 2-15b). Where unit C is present, sand-rich distributary channel and channel-mouth bar deposits and thin mudstone lenses characterize unit E. These record deposition along open stretches of the coastline where wave processes were dominant and closely resemble wave-dominated successions described by others (DeCelles, 1986; Leckie and Walker, 1982; Leithold and Bourgeois, 1984). Sand supplied to the strand by distributary channels was reworked by shoaling fairweather waves and deposited as distributary-mouth bar and beach-ridge deposits. This is a commonly observed process in wave-dominated settings (Elliot, 1986a, 1986b; Heward, 1981; Miall, 1984; McCubbin, 1982; Reinson, 1984). These marginal-marine sands were also subjected to episodic reworking by high-energy storm waves, which resulted in seaward transport and deposition of sand in shallow offshore areas as tempestites. Where unit D is present, distributary channel-fill sequences capped by thick mudstone intervals characterize unit E and record deposition in coastal swamp and/or marsh settings that probably developed along the seaward margin of incised paleovalleys and the landward margin of estuaries (cf. Dalrymple et al.,1992; Kraft ,1971; and Kraft and John ,1979).

As relative sea level rise continued and the strand line gradually transgressed paleotopographically higher areas on the sub-Mississippian unconformity, only a thin veneer of fine- to medium-grained sandstone and organic-rich mudstone accumulated, as recorded in unit F (Figure 2-15b). At most localities in the northeastern Brooks Range where the sub-Mississippian unconformity is exposed, the surface displays little relief, is laterally extensive, and is overlain by a thin veneer of Kekiktuk sediment that is assigned to depositional unit F. Thus, unit F is the record of the most extensive mode of sedimentation preserved in the Kekiktuk and represents deposition above an extensive, low-relief surface in the interfluves discussed in the previous section. This was the last gasp of coarse-grained terrigenous clastic sedimentation in the Kekiktuk Conglomerate as transgression progressed. Remnant local paleohighs that existed locally after this last phase of Kekiktuk sedimentation were eventually drowned and buried beneath shallow-marine mudstones of the Kayak Shale.

The presence of well-preserved beach deposits in unit E, transgressive veneer deposits in unit F, and the pronounced flooding surface at the top of the Kekiktuk suggest that the transgression was rapid. This is consistent with a high rate of relative sea level rise that probably resulted from the combined affects of thermally controlled subsidence and eustatic sea level rise. The limited thickness and widespread areal distribution of the Kekiktuk Conglomerate and its stratigraphic position above an extensive unconformity and below marine shales and carbonate rocks are typical of other transgressive successions deposited landward of the tectonic hinge zone during thermally controlled subsidence in the post-breakup phase in passive continental margin settings (e.g. Allen and Allen, 1990; Dewey and Bird, 1970; James et al., 1989; Mitchell and Reading, 1986; Symonds et al., 1983). We interpret the flooding surface recognized at the top of the Kekiktuk Conglomerate to record the onset of thermally controlled subsidence in a passive continental margin setting.

In our depositional reconstruction, we portray the Kekiktuk-Kayak strand line as non-deltaic (Figure 2-15b), but a deltaic interpretation is also possible. Recognition of deltaic successions in the stratigraphic record depends on recognizing three facies associations, including delta plain, delta front, and delta abandonment (Elliot, 1986a). The upper parts of units C and D could represent deposition in delta plain settings. Upward-coarsening, progradational sequences, which are characteristic of the delta front facies association (Coleman and Prior, 1982; Elliot, 1986a; Galloway and Hobday, 1983; and Miall, 1984), have not been recognized in the Kekiktuk Conglomerate and overlying Kayak Shale. Progradational sequences could have been removed due to wave reworking as relative sea level rose and flooded the region. If this interpretation is correct, unit E could be an incomplete delta front sequence similar to those recognized by Weise (1980) in the Cretaceous San Miguel Formation. Incomplete delta front sequences in the San Miguel Formation were attributed to delta abandonment due to low sediment supply and high rates of relative sea level rise. This is consistent with Galloway and Hobday's (1983) observation that much of the delta front record is destroyed during delta abandonment and transgression. In support of this interpretation, Bloch et al (1990) view the Kekiktuk Conglomerate in the northeastern Brooks Range as the product of a single, large fan-delta system.

Our analysis suggests that the Kekiktuk-Kayak strand line was primarily non-deltaic north of the Continental Divide and east of the Canning River, as shown in Figure 2-15b. The absence of progradational delta front sequences in the Kekiktuk Conglomerate and basal Kayak Shale throughout this area suggest that the supply of coarse-grained sediment to the strand line could not keep pace with the rate of relative sea level rise. If fluvial systems were able to build and prograde deltaic wedges, it seems likely that some evidence of this - such as coarsening- and thicknening-upward sequences - would have been preserved. The well-defined flooding surface recognized at the top of the Kekiktuk Conglomerate throughout much of the region suggests that northward migration of the strandline was rapid, and is consistent with a relatively low supply of coarse-grained sediment and a high rate of relative sea level rise. In contrast, Anderson (1993, personal communication) has recognized deltaic sequences within the uppermost Kekiktuk Conglomerate and basal Kayak Shale in the Continental Divide region to the south. In this region, the Kekiktuk Conglomerate and Kayak Shale were deposited at or very close to the rifted basin margin where the supply of coarse-grained sediment, although intermittent, was relatively high (Anderson, 1993, personal communication). As transgression proceeded northward over the rift flank and upland region of the northeastern Brooks Range, the regional paleoslope and sediment supply gradually decreased, thereby precluding deltaic sedimentation.

Our analysis has important implications for exploration in the subsurface of the Arctic National Wildlife Refuge coastal plain to the north. The Kekiktuk in the subsurface at Endicott Field differs in several respects from its outcrop counterpart to the southeast. In the subsurface, the Kekiktuk is much finer-grained, containing only minor conglomerate, and is considerably thicker, attaining a thickness of 650+ m (Miller, 1991) as opposed to a maximum thickness in outcrop for the Kekiktuk Conglomerate of 128 m (LePain and Crowder, 1992b). Woidneck et al. (1987) noted that the three zones recognized in the subsurface did not correspond to the three members observed in outcrop. They suggested that zone 1 is missing in outcrop and that zones 2 and 3 correspond to the middle and upper members, respectively, of Nilsen et al. (1980, 1981). We see little lithologic similarity between subsurface zones 2 and 3 and the middle and upper members of the Kekiktuk at its type locality, and suggest that the surface and subsurface Kekiktuk successions record deposition in separate basins characterized by different tectonic settings and markedly different regional paleogeographies. Miller (1991) arrived at a similar conclusion based on analysis of electric logs and core of the Kekiktuk Formation and comparison with published descriptions of the

Kekiktuk Conglomerate. Based on these differences, we believe that the Kekiktuk Conglomerate was deposited in an upland region that was not significantly affected by syn-depositional extensional faulting.

The coastal plain of the Arctic National Wildlife Refuge is geographically closer to exposures in the northeastern Brooks Range to the south than to Endicott Field, where the internal organization and depositional history of the Kekiktuk are well-known (Figure 2-4). This suggests that if the Kekiktuk Conglomerate is present in the subsurface of the Arctic National Wildlife Refuge coastal plain, it may differ significantly from its subsurface counterpart to the west at Endicott Field, and have more in common with its outcrop counterpart to the south in the northeastern Brooks Range. If this is true, exploration efforts will have to focus on locating incised paleovalleys above the sub-Mississippian unconformity, where thick coarse-grained fluvial successions would likely be present.

CONCLUSIONS

1. Six depositional units in the Kekiktuk Conglomerate record deposition in a wide range of settings that include low- and high-sinuosity fluvial systems that developed within incised paleovalleys; distributary channels, channel-mouth bar and beach ridge deposits also associated with incised paleovalleys; and sheet-flood and tidal flat/coastal swamp deposits associated with paleotopographically high areas. Distributary channel and channel-mouth bar environments developed at the seaward end of drowned paleovalleys - estuaries.

2. Collectively, these six depositional units record the progressive infilling of modest erosional relief along the sub-Mississippian unconformity; relief on this surface

(erosional and/or fault controlled?) was the primary control on the distribution of depositional units.

3. The region was characterized by gently rolling topography; paleovalleys were localized features that ranged from 10's of meters to ~128 m deep and formed a complex drainage network consistent with deposition in an upland region.

4. Fluvial incision in the northeastern Brooks Range was followed in latest Tournaisian-earliest Visean time by fluvial deposition within incised paleovalleys, initiated due to rise in relative sea level. Paleovalleys were gradually filled and fluvial environments superseded by marginal- and shallow-marine environments as the transgression progressed.

5. Coal-bearing fluvial channel-fill and flood-basin sequences and palynologic data indicate that the latest Tournaisian-Visean climate in the northeastern Brooks Range was humid.

6. The limited thickness, widespread but discontinuous distribution, and organization of the Kekiktuk Conglomerate combined with its stratigraphic position above a regional angular unconformity and below marginal- and shallow-marine shales is consistent with deposition in an upland region situated landward of the tectonic hinge zone in a passive continental margin setting.

CHAPTER 3: MARGINAL-MARINE SEDIMENTATION IN THE LOWER KAYAK SHALE

In the northeastern Brooks Range of Alaska, the Lower Carboniferous Endicott Group is situated at the base of the Ellesmerian sequence, which is separated by the sub-Mississippian unconformity from an underlying weakly metamophosed succession of pre-Middle Devonian sedimentary and igneous rocks (Figure 3-1). The Endicott Group is a transgressive succession that consists, in ascending order, of the Kekiktuk Conglomerate and Kayak Shale (Figure 3-2). In latest Tournaisian time, relative sea-level rise shifted stream equilibrium profiles landward and upward and initiated deposition of the fluvial and marginal-marine Kekiktuk Conglomerate within incised paleovalleys. As relative sea level continued rising, fluvial dispersal systems were gradually drowned and replaced upsection by marginal-marine terrigenous clastic depositional systems recorded in the Kayak Shale. The lower Kayak Shale, as defined informally herein, is restricted to paleogeographic positions above thick valley-filling successions of the Kekiktuk Conglomerate, and consists of organic-rich siltstone, shale, sandstone, and sandy bioclastic limestone. The association of lithofacies recognized within the lower Kayak Shale and presented in this paper suggests the presence of barrier-islands on the seaward side of an estuary or lagoon.

The transition upsection from fluvial to estuarine/lagoonal settings, such as recorded in the Kekiktuk Conglomerate and Kayak Shale, respectively, is a common pattern recognized in many Holocene and ancient transgressive sequences (Bridges, 1976; Franks, 1980; Kraft,

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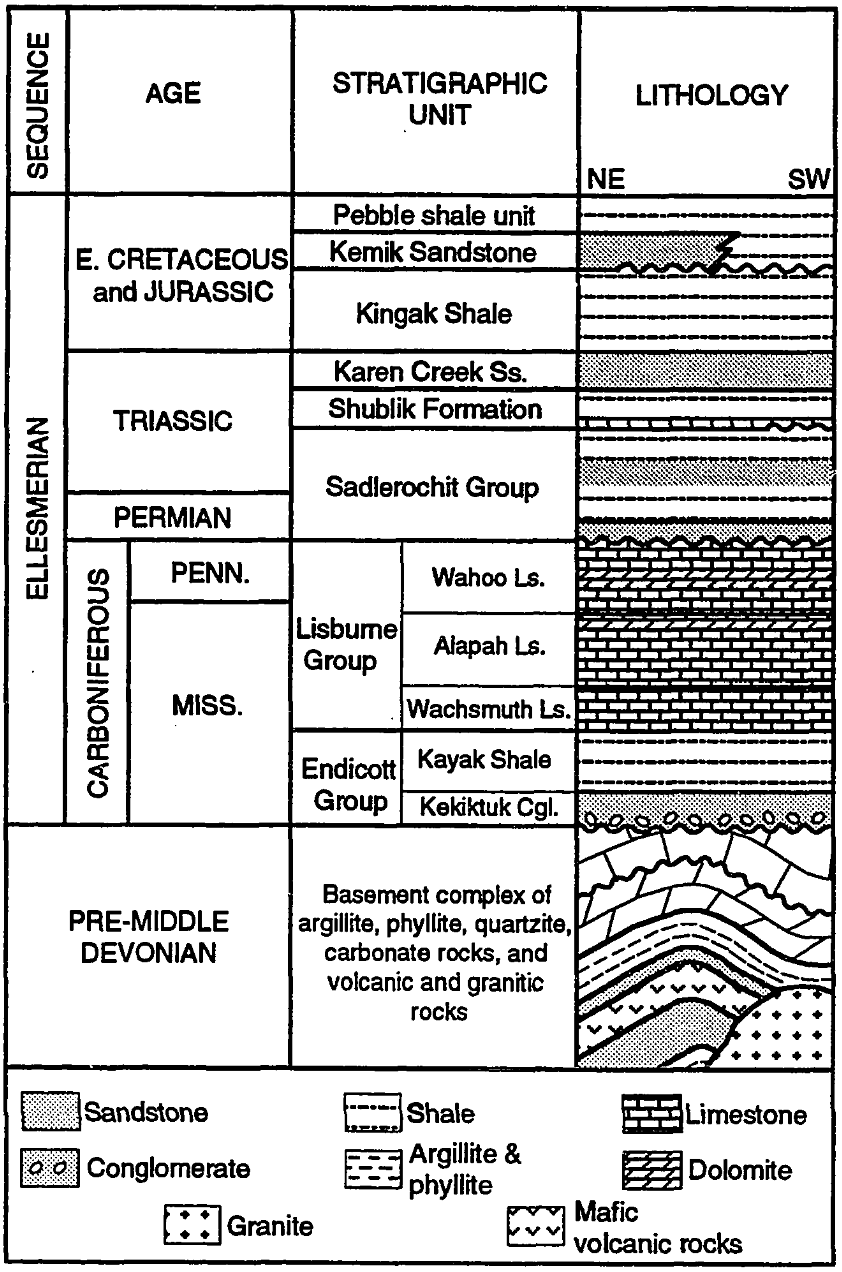

Figure 3-1 - Generalized column of the Ellesmerian sequence in the northeastern Brooks Range. No scale intended. Modified from Bader and Bird (1986).

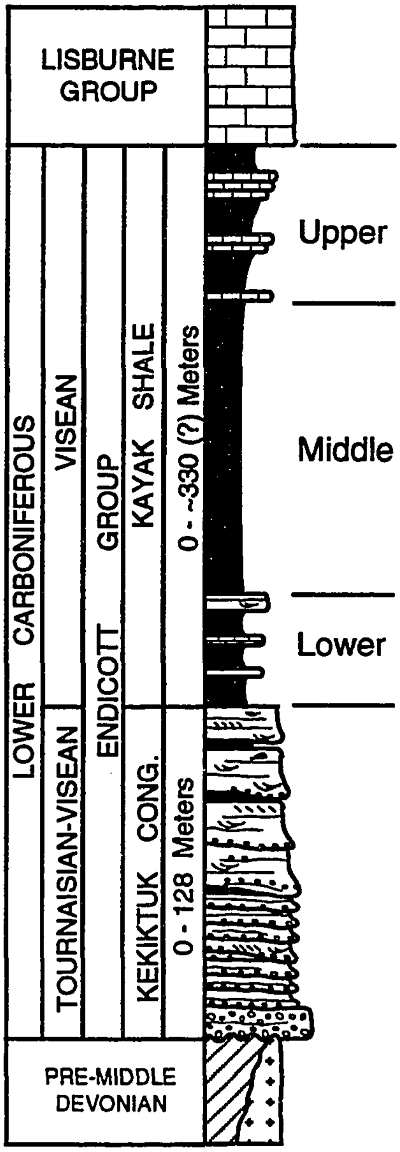

Figure 3-2 - Generalized column of the Endicott Group in the northeastern Brooks Range. No scale intended.

1971; Kraft and John, 1979; Wilkinson, 1975; Wilkinson and Byrne, 1977). In transgressive settings where the supply of coarse-grained sediment is low, barrier-islands migrate landward and are characterized by their poor preservation potential due to shoreface erosion in the surf zone (Fischer, 1961; Swift, 1968). However, Fischer (1961) and Kraft (1971) speculated that it is possible to completely preserve barrier-islands under these conditions if the rate of relative sea-level rise is great enough. Kraft (1971) also observed that barrier-islands situated on the seaward side of drowned valleys have enhanced preservation potential due to their geographic position in topographically low areas. Thus, preservation of transgressive barrier-island sequences has important implications for understanding the character of pre-transgression surfaces, such as the sub-Mississippian unconformity, and the rate of relative sea-level rise. These, in turn, provide insight into the tectonic setting in which the marginal-marine succession originated.

The purpose of this paper is to reconstruct transgressive marginal-marine sedimentation patterns recorded in the lower Kayak Shale in the northeastern Brooks Range and relate these to relief on the sub-Mississippian unconformity surface, the underlying fluvial successions of the Kekiktuk Conglomerate, and regional paleogeography and tectonic setting. After a brief discussion of the geologic setting and overall organization of the Kayak Shale, we describe the vertical, lateral, and internal organization of lithofacies recognized within the lower Kayak Shale and develop a depositional reconstruction.

GEOLOGIC SETTING

In northern Alaska, a regional sub-Mississippian angular unconformity has been recognized throughout the North Slope subsurface and at widely spaced locations across the Brooks Range. This unconformity truncates rocks as young as Early Devonian (Blodgett et al.,

1991) and represents a fundamental change from dominantly contractional deformation below to extensional deformation above (Moore et al., 1992). In the northeastern Brooks Range, the Endicott Group rests above this unconformity and consists of fluvial and marginal- to shallow-marine clastic rocks that are latest Toumaisian to Visean in age (Armstrong and Mamet, 1977; Utting, 1990, 1991a, 1991b). Endicott strata form the base of a northward-onlapping succession (Brosge et al., 1962; Nilsen, 1981) of terrigenous clastic and carbonate strata assigned to the Ellesmerian sequence (Figure 3-1), which is a Lower Carboniferous through Lower Cretaceous south-facing passive continental margin succession.

In the Continental Divide region of the eastern Brooks Range, the Carboniferous Endicott Group is slightly older (Toumaisian to Visean) and is situated unconformably above a thick Middle to Upper (?) Devonian terrigenous clastic succession (Anderson et al., 1992). The Devonian and Lower Carboniferous successions have been interpreted to record the rift and subsequent early drift phases, respectively, in the formation of a passive continental margin by Anderson and Wallace (1991) and Anderson et al. (1992). Farther south of the Continental Divide in the eastern Brooks Range, and throughout the central and western Brooks Range, a stack of south-derived allochthons contain Upper Devonian through Lower Cretaceous rocks (Mull, 1982; Moore et al., 1992). Many workers believe these to be elements of a succession deposited on a late Paleozoic, south-facing passive continental margin (Moore et al., 1992). The structurally lowest allochthon, referred to as the Endicott Mountains allochthon (Mull, 1982), contains a thick Upper Devonian to Lower Carboniferous clastic wedge that consists of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale (Moore et al., 1992). This wedge records progradation to the south and southwest of major fluvial-deltaic depocenters that formed along the Late Devonian-Early Carboniferous basin margin (Moore and Nilsen, 1984; Moore et al., 1992). Middle and Upper Devonian terrigenous clastic rocks are missing in the northeastern Brooks Range. These regional relationships combined with the limited thickness, widespread distribution, and stratigraphic position of the Kekiktuk Conglomerate below the marginal- and shallow-marine Kayak Shale strongly suggest that the Carboniferous Endicott Group in the northeastern Brooks Range records deposition in an upland area situated landward of the tectonic hinge zone on a subsiding passive continental margin.

In the northeastern Brooks Range, the Kekiktuk Conglomerate is thickest in incised paleovalleys and progressively thins toward, and eventually pinches out against, adjacent paleotopographic highs (LePain and Crowder, 1992b). These relationships indicate that where the Kekiktuk Conglomerate is thickest, fluvial systems were confined within incised paleovalleys cut into pre-Middle Devonian rocks and, where only a thin veneer of Kekiktuk is present, it is the record of deposition over paleotopographic highs on the sub-Mississippian unconformity (LePain and Crowder, 1992b). Post-rift subsidence of continental crust landward of the hinge zone (e.g. Braun and Beaumont, 1989), combined with eustatic sea level rise throughout Early Carboniferous time (Hallam, 1984), resulted in regional transgression, flooding of fluvial dispersal systems, and establishment of a broad suite of marginal- and shallow-marine depositional environments recorded in the Kayak Shale.

In the northeastern Brooks Range, Cenozoic contractional deformation has resulted in several east-west trending anticlinoria (Wallace and Hanks, 1990). The Kayak Shale and associated strata crop out along the flanks of these anticlinoria (Figure 3-3).

ORGANIZATION OF THE KAYAK SHALE

Bowsher and Dutro (1957) named the Kayak Shale for ~290 m of Lower Carboniferous marine black and dark gray shale, siltstone, sandstone, and argillaceous limestone that is

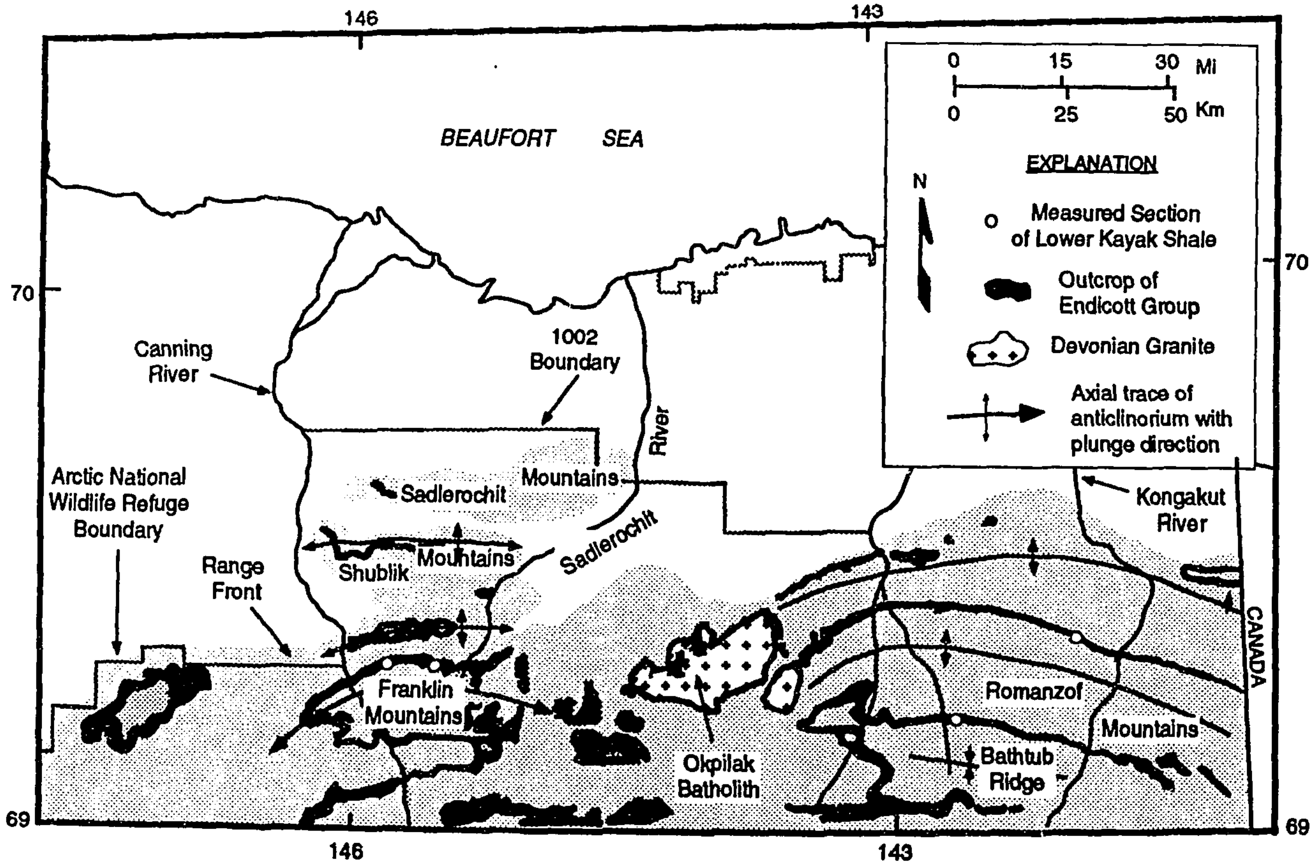

Figure 3-3 - Map showing distribution of Endicott outcrop belts in the northeastern Brooks Range. Circles show location of measured sections. Modified from Bird et al. (1987).

exposed in the central Brooks Range. At its type locality, the Kayak is Toumaisian in age (Armstrong and Mamet, 1977), situated disconformably above the Upper Devonian-Lower Carboniferous Kanayut Conglomerate, and disconformably below the Lisburne Group. Bowsher and Dutro (1957) recognized five informal members in the Kayak Shale including, in ascending order, a basal sandstone, lower black shale, argillaceous limestone, upper black shale, and a red limestone. Brosge et ai. (1962), while working on the Paleozoic sequence in the eastern Brooks Range, recognized a similar black shale succession below the Lisburne Group in exposures east of the Canning River. They considered it to be of Lower Carboniferous age, and referred to it as the Kayak (?) Shale. Following current stratigraphic terminology, we refer to this succession as the Kayak Shale.

We have divided the Kayak Shale into three informal members based on lithology and their relationship to the sub-Mississippian unconformity, the Kekiktuk Conglomerate, and the overlying Lisbume Group (Figure 3-2). The lower Kayak Shale has been recognized at only a few locations in the northeastern Brooks Range and is restricted to positions above thick, mud-rich, valley-filling fluvial to marginal-marine successions of the Kekiktuk Conglomerate. The contact between the lower Kayak Shale and the underlying Kekiktuk Conglomerate is typically poorly exposed, but appears to be gradational. The lower Kayak Shale consists predominantly of organic-rich mudstone, quartzose sandstone, quartzose bioclastic limestone, and minor anthracitic coal.

The middle Kayak Shale is present throughout the northeastern Brooks Range where a variety of contact relationships have been observed with underlying rocks. The contact between the lower and middle Kayak Shale is sharp. Where the lower Kayak Shale is absent, both sharp and gradational contacts have been observed between the middle Kayak and the underlying Kekiktuk Conglomerate. Where the Kekiktuk Conglomerate is absent above paleotopographic highs, the middle Kayak Shale rests unconformably on pre-Middle Devonian rocks. The middle Kayak Shale consists predominantly of black to dark gray shale. Minor anthracitic coal and sharp-based sandstone beds and bedsets are locally present near the base of the middle Kayak.

The contact between the middle and upper Kayak Shale is gradational. The upper Kayak consists of dark gray to black, organic-rich shale and a variety of carbonate lithologies. The upper Kayak Shale records the transition from terrigenous clastic-dominated environments of the Endicott Group to carbonate-dominated environments of the overlying Lisburne Group.

LITHOFACIES IN THE LOWER KAYAK SHALE

A broad suite of seven lithofacies has been recognized in the lower Kayak on the basis of lithology and sedimentary and biogenic structures. Descriptions and interpretations of depositional processes and environments are presented in this section in ascending stratigraphic order for each lithofacies. The organization of the lower Kayak is summarized in Figure 3-4 and summary lithofacies descriptions are presented in Table 3-1. We interpret the lower Kayak Shale as the depositional record of a barred estuarine system. However, many of the physical attributes of the lithofacies presented herein are not unique to any specific environmental setting - estuarine or otherwise. It is the association of lithofacies and their relationships to the underlying Kekiktuk Conglomerate and the pre-Mississippian unconformity that suggest an estuarine depositional setting.

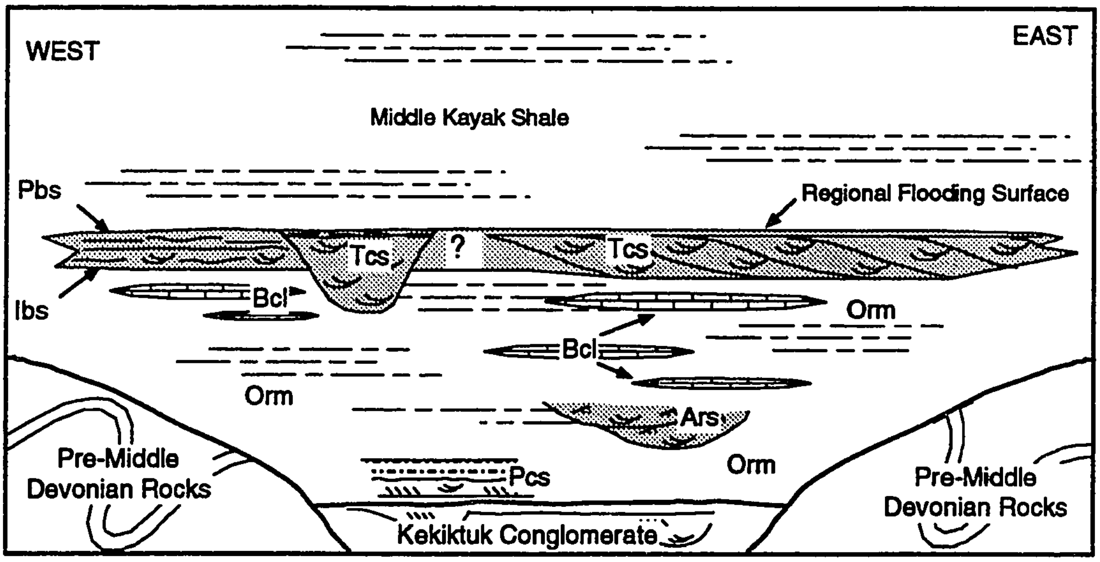

Figure 3-4 - Schematic cross-section across valley-fill in the northern Franklin Mountains summarizing lateral and vertical lithofacies relations in the lower Kayak Shale. Lithofacies symbols: Ars = argillaceous sandstone, Bcl = bioclastic limestone, Ibs = irregularly bedded sandstone, Orm = organic-rich mudstone, Pbs = plane-bedded sandstone, Pcs = planar cross-bedded sandstone, Tcs = trough cross-bedded sandstone.

Table 3-1 - Summary descriptions of lithofacies in the lower Kayak Shale.

Lithofacies	Composition & Texture	Sedimentary & Biogenic Structures	Geometry & Position	Interpretation
Organic-rich mdst. (Orm)	Black, organic-rich siltstone, silty shale, and shale, minor fine-grnd. quartzose sandstone, +- plant frags and coal.	Fissile mudstone, +- lenticular laminated sandstone	Geometry unknown; valley-fill, lower cont. with Kekiktuk not exposed, but appears gradational.	Estuary with fringing swamps or marshes on landward side.
Planar x-bedded ss. (Pcs)	Qtz arenite and chert-qtz sub-litharenite (lower unit), lithic wacke (upper unit).	Wavy, parallel beds up to 15 cm thick; planar x-beds in sets 6-15 cm thick, reactivation surfaces; trough x-beds in sets up to 10 cm thick; mudstone partings between most foreset beds; upper unit is burrow mottled.	Geometry unknown; encased in organic-rich mdst., near base of lower Kayak.	Tidal sandflat and tidal creek.
Argill. ss. (Ars)	Qtz arenite, chert-qtz sub-litharenite, and chert-qtz gran. conglom.	Lower cont. w/ organic-rich mdst. is erosive, upper is sharp to gradational; at least two fining-upward cycles; trough x-beds 10-30 cm thick; ripple x-laminae; mudstone intraclasts throughout; scale of sedimentary structures decreased upward.	Lenticular geometry; encased within organic-rich mdst., near base of lower Kayak.	Channelized fluvial-flood succession.
Bioclastic ls. (Bcl)	Qtzose bryozoan-pelmat. packstone and grainstone.	Sharp lower cont. with organic-rich mdst.; normally graded; pref. orientation of skel. grns; skel. grns. highly abraded; variably bioturbated.	Lenticular; encased within organic-rich mdst., near middle and top of lower Kayak.	Distal storm-washover deposits.
Irreg. bedded ss. (Ibs)	Qtz arenite.	Discont., wavy beds up to 6 cm thick; trough x-beds up to 5 cm thick; horizontal traces on bedding planes - resemble *Thalassanoides* and *Ophiomorpha*.	Sharp lower cont. with organic-rich mdst., sharp upper cont. with plane-bedded ss. at top of lower Kayak, truncated laterally by trough x-bedded ss.; geometry unknown, broadly lenticular (?);	Back-barrier proximal washover deposits.
Plane-bedded ss. (Pbs)	Qtz arenite.	Even parallel beds up to 3.0 cm thick; low-angle inclined lamination; low-relief scours; parting lineation on some bed surfaces.	Sharp lower cont. with irregularly bedded ss., sharp upper cont. with middle Kayak, truncated laterally by trough x-bedded ss.	Lower foreshore to upper shoreface deposits.
Trough x-bedded ss. (Tcs)	Qtz arenite.	Large-scale trough x-beds in sets up to 1.0 m thick; plane-parallel beds at top of succession up to 20 cm thick.	Sharp lower cont. with organic-rich mdst., sharp upper cont. with middle Kayak; lenticular.	Tidal inlet-fill deposits.

Organic-Rich Mudstone

The organic-rich mudstone lithofacies is up to 65 m thick and encases most of the other lithofacies in the lower Kayak (Figure 3-4). The contact between this lithofacies and the underlying Kekiktuk Conglomerate is generally poorly exposed, however, based on the character of float, it is most likely a gradational relationship. This lithofacies consists of dark gray-to-black, organic-rich siltstone, silty shale, and shale and weathers into elongate, pencil-like fragments (Figure 3-5 and Table 3-1). Siltstone is most common in the lower beds of this lithofacies. Locally, mudstones contain conspicuous red-brown weathering, disc-shaped calcitic and pyritic concretions up to 12 cm thick and 31 cm in diameter. Lenticular laminae <0.5 cm thick of fine-grained quartzarenite are scattered throughout this lithofacies. Minor anthracitic coal is present near the base of this lithofacies. Moderately well-preserved plant fragments up to 15 cm long are restricted to the lower half of this lithofacies, while comminuted organic debris is common in mudstones of the upper half. Palynologic samples collected from this lithofacies contain abundant woody and coaly fragments (Utting, 1990). Scolecodonts, the jaw apparatus of a marine annelid worm, have been identified in mudstone samples (Utting, 1990).

The organic-rich mudstone lithofacies records deposition from suspension in a low-energy estuarine setting. Relatively abundant siltstone near the base of this lithofacies records proximity to fluvial channels or tidal creeks. Siltstone and lenticular laminated sandstone record deposition from weak traction currents that were associated with discharge from fluvial channels recorded in the underlying Kekiktuk Conglomerate. The progressively lower siltstone content up-section indicates a steadily decreasing supply of coarser-grained detritus to the estuarine environment. Thin lenticular laminae of fine-grained sandstone may indicate fluctuating energy levels associated with tides. Lenticular bedding is a common

Figure 3-5 - Photograph of the lower Kayak Shale. Prominent sandstone body in center of photograph is the trough cross-bedded sandstone lithofacies, which marks the top of the lower Kayak Shale. View looking toward the north, approximately 2 km west of Straight Creek, in the northern Franklin Mountains. From base of dip-slope to top of sand body is 64 m.

feature in tidally influenced settings (Reineck and Wunderlich, 1968). Minor anthracitic coal lenses and abundant plant fragments in the lower half of this lithofacies suggest that swamps existed on the landward side of the estuary and that deposition in these areas proceeded at, or very close to, sea-level under anaerobic conditions (Galloway and Hobday, 1983). The dark gray and black coloration indicates an organic carbon content >1.0% (Hosterman and Whitlow, 1983; Potter et. al., 1980) and that the estuary was characterized by an oxygen-depleted bottom layer (Heckel, 1972). Scolecodonts are the only indigenous faunal remains recognized in this lithofacies, which suggests that bottom conditions were at least dysaerobic locally and capable of supporting some life (O'Brien and Slatt, 1990).

Planar Cross-Bedded Sandstone

The planar cross-bedded sandstone lithofacies is ~1.5 m thick, has only been recognized at one locality, and is poorly exposed near the base of the lower Kayak Shale (Figures 3-4 and 3-6). This lithofacies consists of medium- to coarse-grained sandstone and argillaceous sandstone and can be divided into two units based on mudstone content. The lower unit is ~1.0 m thick and consists of moderately sorted, medium- to coarse-grained sandstone. Sandstones contain both planar tabular and tangential cross-bedded sets from 6 to 15 cm thick, and minor trough cross-bedded sets up to 10 cm thick (Figure 3-6). Planar cross-beds overlie an erosion surface with up to 5 cm of relief and are unidirectional. Reactivation surfaces have been recognized between some sets. The total mudstone content is low, although mudstone drapes are commonly observed between foreset laminae and small mudstone intraclasts are common throughout.

The upper unit is 0.5 m thick, rests in sharp contact with the lower unit, and is sharply overlain by the organic-rich mudstone lithofacies. This unit consists of highly bioturbated,

Figure 3-6 - Photograph of the planar cross-bedded sandstone lithofacies. View looking toward the northeast. Note glove in left-center of photograph for scale (23 cm long).

poorly sorted, fine- to medium-grained, argillaceous sandstone. Mudstone is present throughout, beds are wavy, discontinuous and up to 4 cm thick.

Sequences resembling the planar cross-bedded lithofacies have been described from siliciclastic tidal-flats by Raaf and Boersma (1971), Reineck (1972), and Weimer et al. (1982). Planar and trough cross-bedded sandstone in the lower unit record the migration of straight-crested sandwaves and sinuous-crested dunes, respectively, under lower flow-regime conditions (Harms et al., 1982). Mudstone drapes between some foreset laminae indicate deposition during slack water periods in the middle of tidal cycles when currents were weak or non-existent. These are analogous to mud drapes observed in sand successions from modern tidal-flat environments by Raaf and Boersma (1971). Associated reactivation surfaces are consistent with deposition in a tidal-flat environment, where they are commonly associated with sandy successions deposited from reversing tidal currents with asymmetric time-velocity profiles (Raaf and Boersma, 1971; Reineck and Singh, 1980). The highly bioturbated, argillaceous character of the upper unit is consistent with this interpretation and resembles highly bioturbated tidal deposits described by Raaf and Boersma (1971). The vertical succession indicates progressive flooding and gradual drowning of a sandy tidal-flat.

Argillaceous Sandstone

The argillaceous sandstone lithofacies is ~3.5 m thick, weathers to a dark red-brown color, and has only been recognized at one locality where it is situated near the base of the lower Kayak Shale (Figures 3-4 and 3-5). This lithofacies has a broad, lenticular geometry and consists of argillaceous, quartzose granule conglomerate and fine- to coarse-grained sandstone in beds from 4 to 50 cm thick (Table 3-1). In vertical succession, this lithofacies is composed of at least two upward-thinning and -fining cycles from 1.0 to 2.5 m thick. The lower cycle consists of a basal, trough cross-bedded quartz-granule conglomerate that rests above a sharp, erosive contact with the underlying organic-rich mudstone lithofacies (Figure 3-7). Conglomerate is gradationally overlain by trough cross-bedded and ripple cross-laminated, fine- to coarse-grained sandstone. Elongated black, organic-rich mudstone intraclasts are common throughout the cycle and are oriented parallel to bedding. The higher cycle erosively overlies and is similar in all respects to the lower cycle, with the exception that a basal conglomerate is lacking and the cycle is sharply overlain by dark gray to black mudstone. Within both cycles, the scale of sedimentation units gradually decreases upsection while the degree of bioturbation increases. Poorly preserved plant fragments are present on some bedding surfaces.

The low stratigraphic position of this lithofacies within the lower Kayak Shale, the sharp, erosive basal contact, and the fining- and thinning-upward vertical trend in each individual cycle suggests that the argillaceous sandstone lithofacies records at least two episodic events. Each event was characterized by an initial high-energy phase when turbulent currents reworked underlying mud. Currents traversed a cohesive, muddy substrate, as indicated by the ubiquitous presence of mudstone intraclasts. After the initial scour phase, the record is one of gradually waning flow strength. Within each cycle, coarse-grained detritus initially migrated as small- to medium-scale sinuous-crested dunes under lower flow-regime conditions (Harms et al., 1982). As flow strength gradually decreased, progressively finer-grained sediment was deposited in smaller-scale bedforms until, at the end of each cycle, fine-grained sandstone was deposited from migrating asymmetric, sinuous-crested ripples. The vertical succession in the argillaceous sandstone lithofacies closely resembles fining-upward channel-fill sequences described from fluvial settings by Allen (1964; 1970), Cant (1982), and

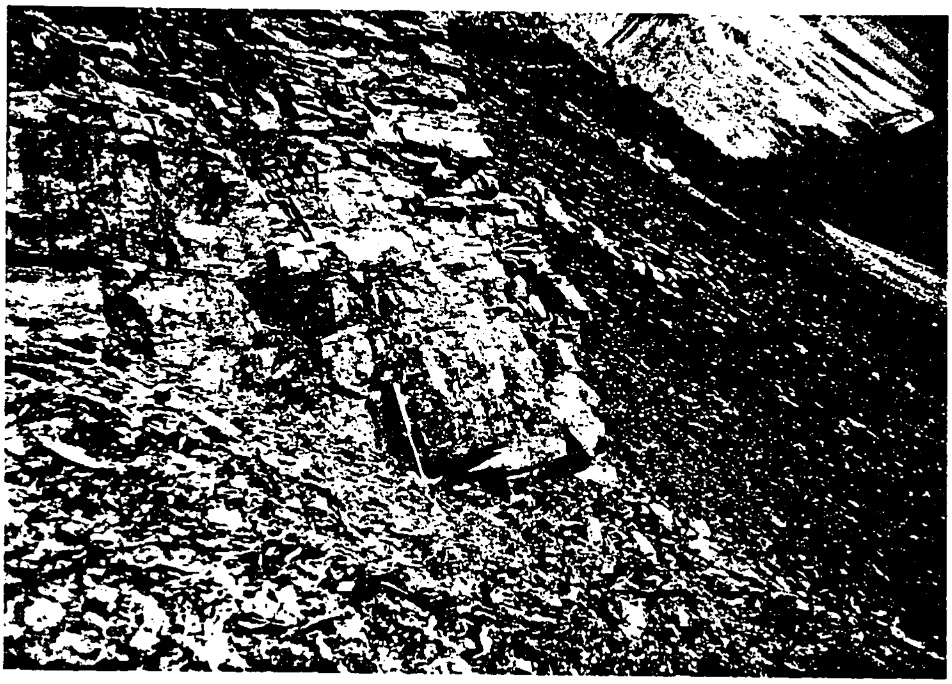

Figure 3-7 - Photograph of the argillaceous sandstone lithofacies. Note sharp basal contact with the organic-rich mudstone lithofacies and the thinning-upward trend in bedding. Hammer in center of photograph is 45 cm long.

Walker and Cant (1984). The close association between the argillaceous sandstone lithofacies and underlying coarse-grained valley-filling fluvial successions in the Kekiktuk Conglomerate suggests that the former record episodic transport of coarse-grained detritus into a marginal-marine setting during fluvial flood events. They appear similar to proximal bayhead-delta sequences in estuarine successions described by Dalrymple et al. (1992) and shoreline fan-delta deposits recognized in Lower Silurian barrier-island successions in southwest Wales by Bridges (1976).

Bioclastic Limestone

The bioclastic limestone lithofacies consists of red-brown weathering limestone lenses up to 1.2 m thick that extend 5 to >50 m along local strike within the upper beds of the lower Kayak Shale (Figures 3-4, 3-5, and Table 3-1). Limestone lenses have sharp, erosive lower and sharp upper contacts with organic-rich mudstone and usually consist of several thin laminasets (Figure 3-8). Laminasets are up to 6 cm thick and separated by thin shale partings. Locally, lenses are composed of bedsets with individual beds up to 6 cm thick that lack shale partings and have erosive bounding surfaces. Many of the thicker beds are normally graded. Limestones consist primarily of bryozoan and pelmatozoan packstone and grainstone with subordinant brachiopods, pelecypods, rugose corals, ostracods, trilobites, calcispheres, mudstone intraclasts, and angular-to-subround sand- and granule-sized detrital quartz (Figure 3-9). Mudstone intraclasts and elongate skeletal grains have a strong preferred orientation parallel to bedding, and the latter are highly broken and abraded. The upper surfaces of some lenses and stratal units comprising lenses are slightly bioturbated to completely burrow-mottled. Where well-exposed, the quartzose bioclastic limestone lenses clearly define a thickening-upward trend (Figure 3-5).

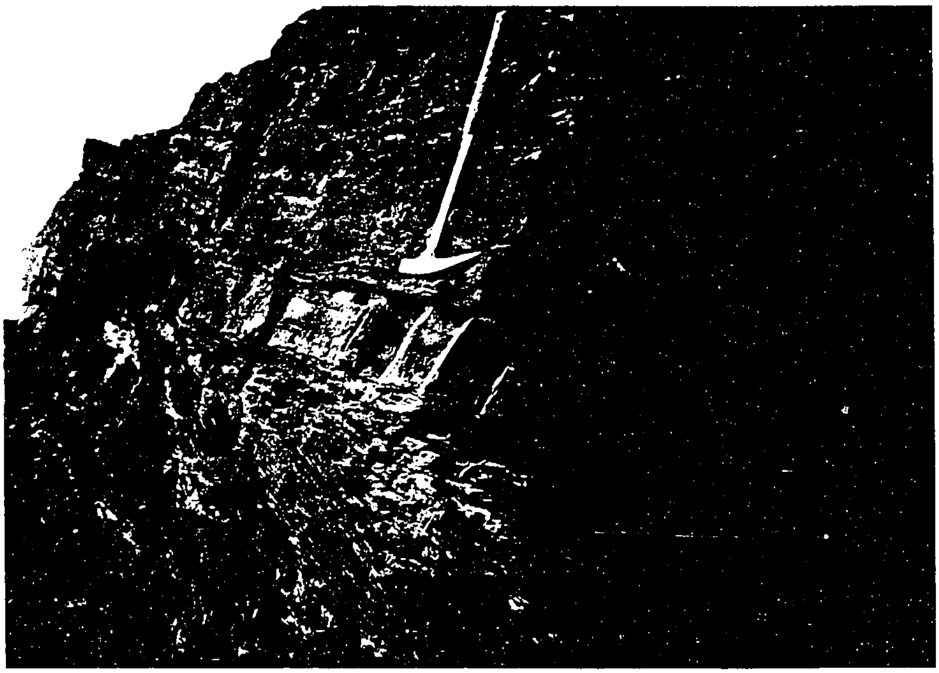

Figure 3-8 - Photograph of bioclastic limestone lithofacies. Note sharp basal contact and shale partings throughout the bedset. Hammer is 45 cm long.

Figure 3-9 - Photomicrograph of bioclastic limestone lithofacies. Note coarse-grained sand in packstone/grainstone. Large skeletal fragment in lower right of photograph is recrystallized brachiopod. Scale is 1 cm = 1.47 mm.

The quartzose bioclastic limestone lithofacies records episodic sedimentation from storm-generated surges as distal washover deposits (Elliot, 1986b; Reinson, 1984). Normal size grading, broken and abraded skeletal grains, mudstone intraclasts, and the strong preferred orientation of elongate grains parallel to bedding suggest transportation by strong currents, probably under upper flow-regime plane-bed conditions, and are features commonly recognized in storm-generated shell beds (Aigner, 1985; Kreisa and Bambach, 1982). The dark-gray to-black, organic-rich mudstone lithofacies suggests that the estuarine environment was not a suitable habitat for the open-marine fauna contained in these deposits (Flugal, 1982; Heckel, 1972; Wilson and Jordan, 1983). Thus, skeletal grains were transported landward from nearby open-marine settings and deposited in an estuarine environment that was characterized by poor circulation and anaerobic-to-dysaerobic bottom conditions. Detrital quartz grains were entrained by these flows as they overtopped barrier-islands located on the seaward side of estuaries. Storm-generated washover deposits with open-marine, allochthonous faunas have been described from Lower Silurian transgressive barrier-island successions in southwest Wales by Bridges (1976). Storm washovers are most common on microtidal to low mesotidal coasts (Hayes, 1979).

Irregularly Bedded Sandstone

The irregularly bedded sandstone lithofacies is up to 2 m thick and is situated near the top of lower Kayak, where it gradationally overlies organic-rich mudstones and is sharply overlain by the plane-bedded sandstone lithofacies (Figure 3-4). The irregularly bedded sandstone lithofacies consists of fine- to coarse-grained, moderately to well-sorted sandstone in discontinuous beds up to 6.0 cm thick that contain both plane-parallel and trough cross-stratification (Table 3-1; Figure 3-10). Vertical and bed-parallel biogenic traces of uncertain

Figure 3-10 - Photograph of irregularly bedded sandstone lithofacies. Upper part of hammer handle is 26 cm long.

affinity are present on many bedding surfaces. Bed-parallel traces are linear, stand in relief ~1.0 cm, and are up to 2.0 cm wide. Non-branching bed-parallel forms are most common, although branching forms have been observed. Traces resemble *Thalassanoides* and *Ophiomorpha* (Hantzschel, 1975).

The irregularly bedded sandstone lithofacies records episodic events that involved transport of medium- to coarse-grained sand and deposition as proximal washover deposits on the landward side of barrier-islands. The presence of plane-parallel and trough cross-bedding suggests deposition under fluctuating energy conditions. Plane-parallel bedding probably originated under upper flow-regime, plane-bed conditions, whereas, trough cross-bedding developed under lower flow regime conditions from small- to medium-scale dune bedforms (Harms et al., 1982). The gradational lower contact with mudstone indicates progressive landward migration of the lithofacies with repeated depositional episodes. Similar sequences have been described from Holocene back-barrier settings by Hayes and Kana (1976), Kraft (1971), Kraft and John (1979), and Wilkinson (1975). Trace fossils are thought to belong to the Skolithos ichnofacies, which is usually associated with shifting substrates in high-energy settings (Frey and Pemberton, 1984).

Plane-Bedded Sandstone

The plane-bedded sandstone lithofacies is situated at the top of the lower Kayak Shale where it is sharply overlain by the middle Kayak Shale (Figure 3-4). The lower contact with the irregularly bedded sandstone lithofacies is sharp and erosive. This lithofacies is up to 1.0 m thick and consists of medium- to coarse-grained sandstone. Beds are thin (up to 3.0 cm thick), laterally continuous, and commonly contain internal low-angle inclined lamination. Beds are commonly truncated by low-relief scour-and-fill structures (Figure 3-11). Parting lineations are visible on some bed surfaces.

Plane-parallel stratification and parting lineations in medium- to coarse-grained sand are good indicators of upper-flow regime conditions (Collinson and Thompson, 1988; Harms et al., 1982). Low-angle inclined laminae are commonly observed in the foreshore and upper shoreface zones of beaches and are thought to form under upper flow-regime conditions associated with wave swash runoff (Clifton, 1969). All of these structures are present in the plane-bedded sandstone lithofacies, which suggests similar depositional conditions - in the foreshore or upper shoreface zones in a beach setting. The stratigraphic position above organic-rich, coal- and scolecodont-bearing mudstone (organic-rich mudstone lithofacies) and storm-generated quartzose bioclastic limestone and sandstone deposits (bioclastic limestone and irregularly bedded sandstone lithofacies, respectively) suggests deposition on the seaward side of a barrier-island. Similar sequences have been described from barrier-island settings by Hayes and Kana (1976), Kraft (1971), Kraft and John (1979), and Wilkinson (1975). We interpret the sharp contact separating this lithofacies from the underlying irregularly bedded lithofacies as a transgressive disconformity that developed from shoreface erosion in response to relative sea level rise and a gradually decreasing sediment supply to the strand (e.g. Fischer, 1961; Swift, 1968).

Trough Cross-Bedded Sandstone

The trough cross-bedded sandstone lithofacies rests above the organic-rich mudstone lithofacies along an erosional surface at the top of the lower Kayak Shale (Figures 3-3-4, 3-5, and 3-12). At one locality, the trough cross-bedded sandstone lithofacies truncates both the irregularly bedded and plane-bedded sandstone lithofacies and extends several

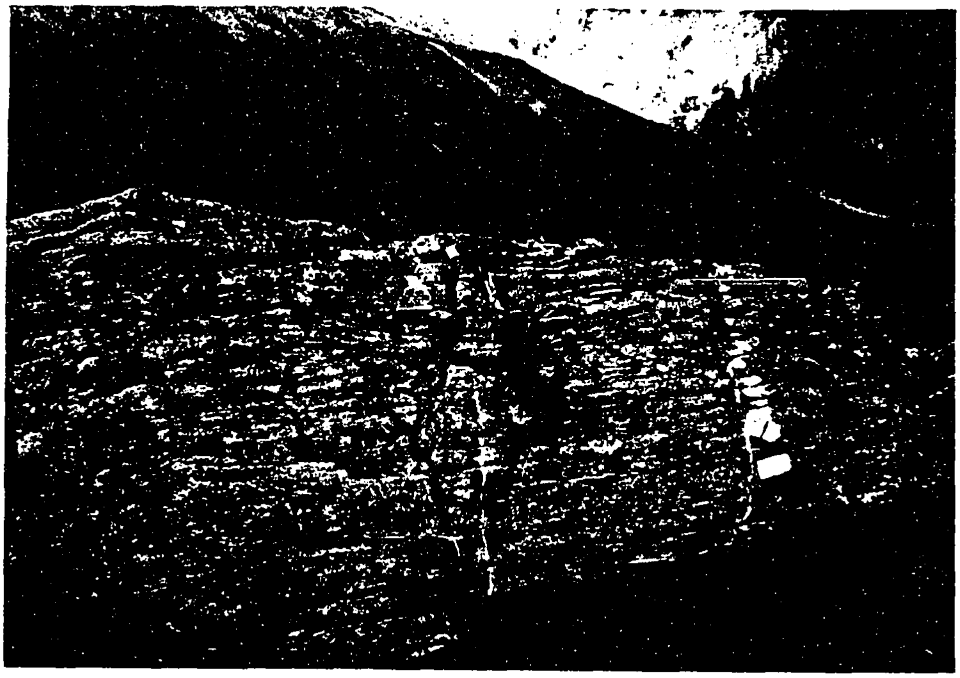

Figure 3-11 - Photograph of plane-bedded sandstone lithofacies. Note shallow scour surface near the top of the hammer handle. Hammer is 45 cm long.

Figure 3-12 - Photograph of trough cross-bedded sandstone lithofacies.

meters into the underlying mudstones (Figure 3-12). At another locality, where the irregularly bedded and plane-bedded lithofacies are absent, the trough cross-bedded sandstone lithofacies forms a laterally extensive lithosome with large-scale lateral accretion surfaces (sandstone body at top of lower Kayak in Figure 3-5). The trough cross-bedded sandstone lithofacies is up to 11 m thick and consists of medium- to coarse-grained, commonly granule-bearing sandstone and minor granule conglomerate.

Conglomerate beds are up to 1.0 m thick and are restricted to the base of this lithofacies. Where conglomerate is present, an upward-fining textural trend is apparent, grading from conglomerate to medium- to coarse-grained sandstone. Most clasts are of extrabasinal origin (quartz and minor chert), however, distinctive mudstone intraclasts are present as elongate chips up to 7 cm long and 1.0 cm thick oriented parallel to stratification. Trough cross-bedding is ubiquitous with individual sets from 0.4 to 0.5 m thick. Foresets are 0.5 to 1.5 cm thick and are usually separated by thin drapes of black mudstone.

Sandstone beds are up to 1.3 m thick and characterized by festoon trough cross-bedding with sets from 0.4 to ~1.0 m thick. Mudstone intraclasts are common and are oriented parallel to stratification. Foreset beds are commonly separated by thin drapes of black mudstone. Scour troughs are 2.5 to 5.0 m wide and one was traced ~25 m in the transport direction. An interval of plane-parallel bedded sandstone from 0.3 to 0.5 m thick usually caps this lithofacies. Both grainsize and the scale of stratification decrease slightly upsection.

The close association between this lithofacies and the irregularly bedded and plane-bedded sandstone lithofacies and its position at the top of the lower Kayak Shale (Figure 3-4) suggest deposition in tidal inlets. Large-scale trough cross-bedding and the coarse grainsize typical of this lithofacies suggest deposition under upper-lower flow-regime conditions from migrating dunes (Harms et al., 1982). Dunes are commonly recognized bedforms in tidal inlets

(Elliot, 1986b; Reinson, 1984). Mudstone drapes separating many foreset beds indicate fluctuating energy conditions between times when flow strength was great enough to transport granule-size clasts and times when flow strength was weak, or non-existent, thereby allowing silt- and clay-sized particles to settle out of suspension and form mudstone drapes. Mudstone drapes are a common feature in sandstones deposited in tidally influenced settings (e.g. Elliot, 1986b; Raaf and Boersma, 1971).

The trough cross-bedded sandstone lithofacies records deposition in two types of tidal-inlet. A deep, stable inlet is indicated where the trough cross-bedded sandstone lithofacies has truncated the barrier-island succession and cut into underlying mudstones. Tidal channels that scour below the level of associated barrier-island deposits into underlying clay substates tend to migrate slowly or remain fixed in one place (Elliot, 1986b). An unstable, or laterally migrating inlet is indicated where the barrier-island succession is absent and the trough cross-bedded sandstone lithofacies is present as an extensive sheet-like lithosome. Inlet-fill of this type contains large-scale lateral accretion surfaces that indicate an easterly migration direction. Lateral accretion surfaces are commonly observed in tidal-inlet successions and record migration of inlets in the direction of longshore currents (Hoyt and Henry, 1967). Tidal- inlet successions may dominate the depositional record of a barrier-island along stretches of coastline with significant longshore currents (Elliot, 1986b).

Swift (1968) suggested that transgressive disconformities bound landward-migrating tidal-inlet successions. Each disconformity represents a ravinement surface and Swift referred to this situation as a double ravinement. Following Swift (1968), two transgressive disconformities are recognized where this lithofacies is present. The lower surface was the result of scour associated with channelized tidal currents and the upper surface resulted from wave reworking in the shoreface zone as the tidal inlet system migrated landward and was gradually abandoned due to relative sea-level rise and a decreasing supply of coarse-grained terrigenous sediment. The upper disconformity is equivalent to the erosional contact between the irregularly bedded and plane-bedded sandstone lithofacies.

DEPOSITIONAL RECONSTRUCTION

Our depositional model for the lower Kayak Shale is summarized in Figures 3-4 and 3-13. Deposition of the Endicott Group was initiated by relative sea-level rise that began to affect the northeastern Brooks Range in latest Tournaisian-earliest Visean time, based on the age of the basal Kekiktuk (Utting, 1991b). Prior to this, downcutting fluvial systems flowed over an uplifted terrane of pre-Middle Devonian sedimentary and igneous rocks and established a system of incised paleovalleys. Relative sea-level rise resulted in an upward and landward shift in stream equilibrium profiles. Thus, fluvial detritus that had previously been flushed toward the south and southwest and incorporated into a thick clastic wedge at the basin margin (Anderson and Wallace, 1991; Nilsen et al., 1980, 1981), gradually became trapped within incised paleovalleys. Thus, the onset of transgression is recorded by deposition of the fluvial Kekiktuk Conglomerate.

The Kekiktuk is present in widespread but discontinuous exposures throughout the northeastern Brooks Range and is thickest in incised paleovalleys (LePain et al., in review). The Kekiktuk either thins drastically or pinches out entirely away from the axial regions of paleovalleys, along the flanks of paleotopographic highs (in paleointerfluves). The lower Kayak Shale has been recognized only above these thick paleovalley-filling successions of the Kekiktuk Conglomerate, which suggests that the distribution of the lower Kayak was directly controlled by paleotopographic relief on the sub-Mississippian unconformity. Onlap relationships between the lower Kayak Shale and underlying pre-Middle Devonian rocks (in

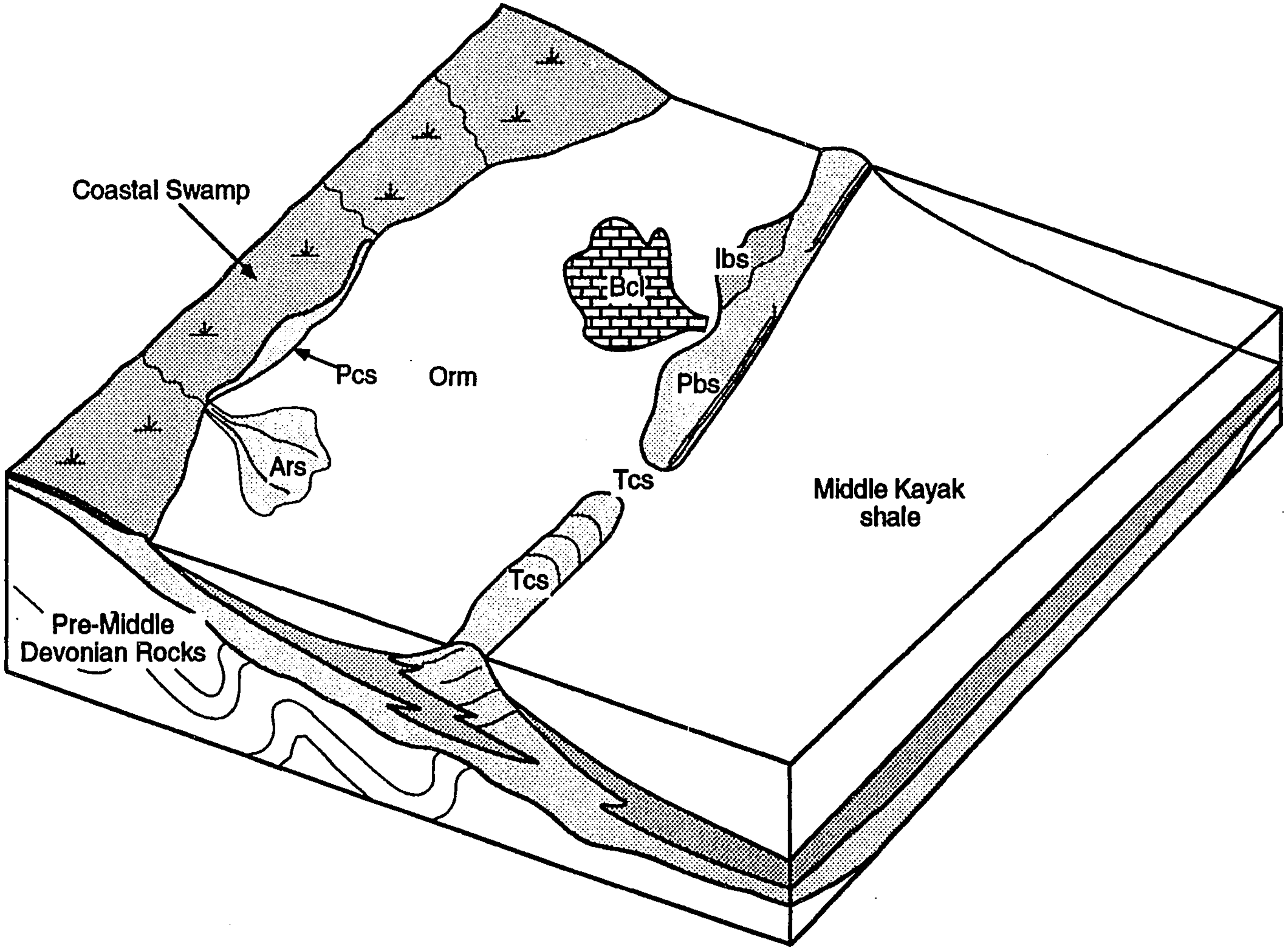

Figure 3-13 - Generalized block diagram of lower Kayak Shale. Orm = organic-rich mudstone lithofacies, Pcs = planar cross-bedded sandstone lithofacies, Ars = argillaceous sandstone lithofacies, Bcl = bioclastic limestone lithofacies, Ibs = irregularly bedded sandstone lithofacies, Pbs = plane-bedded sandstone lithofacies, Tcs = trough cross-bedded sandstone lithofacies.

paleointerfluves) have not been observed, however, the association between the lower Kayak and thick valley-filling successions of the Kekiktuk Conglomerate suggest deposition in an estuarine system (Figure 3-4). The Kekiktuk Conglomerate and lower Kayak Shale were deposited on a surface characterized by significant local relief, at least 128 m (based on maximum thickness of the Kekiktuk Conglomerate) and possibly up to 248 m (maximum thickness of the Kekiktuk Conglomerate plus the thickness of lower Kayak Shale). Paleotopographic relief as a control on distribution of barrier-island and back-barrier successions is well documented for Holocene sediments in Delaware by Kraft (1971) and for Cretaceous marginal-marine rocks in Kansas by Franks (1980). Heward (1981) states that barrier islands have the greatest preservation potential above paleotopographic lows, or drowned valleys.

The degree of preservation of barrier-island and shallow tidal-inlet deposits in the lower Kayak Shale support our conclusion that these systems developed above incised paleovalleys, but also suggest that the transgression was rapid. This could reflect either a low regional paleoslope or a high rate of relative sea-level rise. The transgressive disconformity recognized at the top of the irregularly bedded and trough cross-bedded sandstone lithofacies is interpreted as a marine flooding surface that records drowning and shutdown of marginal-marine depositional systems, and the establishment of shallow-marine conditions.

Under conditions of sea-level rise and low sediment supply, belts of marginal-marine sedimentation shift landward (Fischer, 1961; Swift, 1968). Two contrasting hypotheses have been advanced to describe the response of barrier islands to transgression (Sanders and Kumar, 1975). The most widely accepted is referred to as "shoreface retreat" and involves barriers migrating continuously in a landward direction as shoreface erosion removes part of, or all of, the barrier-island record (Figure 3-14a; Fischer, 1961; Swift, 1968; Sanders and Kumar,

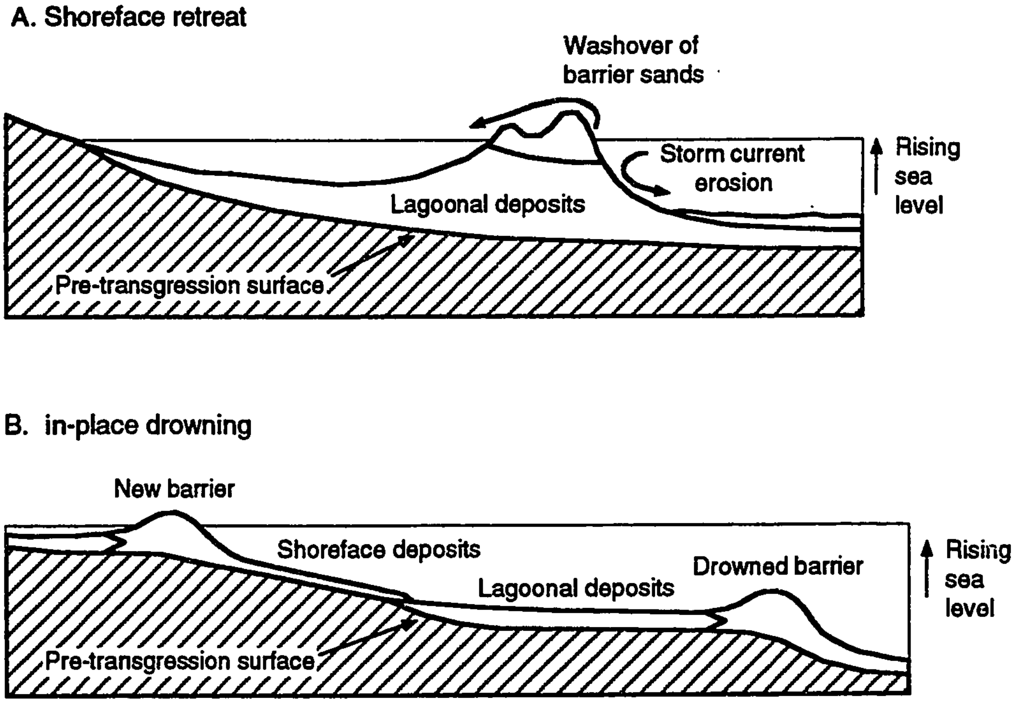

Figure 3-14 - Diagram illustrating barrier migration mechanisms. A) migration due to continuous shoreface retreat, and B) migration due to in-place drowning. Modified from Fischer (1961) and Sanders and Kumar (1975).

1975; Panageotou and Leatherman, 1986). Transgressive barrier-island successions that migrated by "shoreface retreat" should contain a distinctive disconformity created by shoreface erosion. This surface corresponds with Fischer's (1961) intra-sequential disconformity and Swift's (1968) ravinement surface. Sediment derived from barrier islands in this manner is transported both seaward and landward and deposited in lower shoreface and back-barrier settings, respectively (Figure 3-14a).

The second hypothesis has been variously referred to as "in-place drowning" and "stepwise retreat" (Sanders and Kumar, 1975; Rampino and Sanders, 1980; Reinson, 1984). According to this hypothesis, barriers essentially drown in-place with little landward migration and, upon drowning, the surf zone skips landward to the inner side of a lagoon to form a new barrier-island (Figure 3-14b). Barriers that migrated by "in-place drowning" should be recognizeable in the rock record by the presence of a complete transgressive barrier-island succession, including the stratigraphically higher parts of the barrier body (cf. Franks, 1980).

Coarse-grained terrigenous clastic deposits above estuarine mudstones in the lower Kayak Shale suggest that at least part of the barrier-island sand body that developed during the transgression escaped erosion and was incorporated into the stratigraphic record. The preservation of proximal storm washover deposits and shallow tidal-inlet deposits of the irregularly bedded sandstone and trough cross-bedded sandstone lithofacies, respectively, suggests that the rate of relative sea-level rise was great enough to allow partial preservation of the barrier-island record (Figures 3-15). The preservation potential of these barrier islands was also enhanced by paleogeographic positions in incised paleovalleys (cf. Franks, 1980; Kraft, 1971; Wilkinson, 1975). The transgressive disconformity between the irregularly bedded sandstone and plane-bedded sandstone lithofacies and at the top of the trough cross-bedded sandstone lithofacies suggests that part of the barrier-island record was removed by shoreface

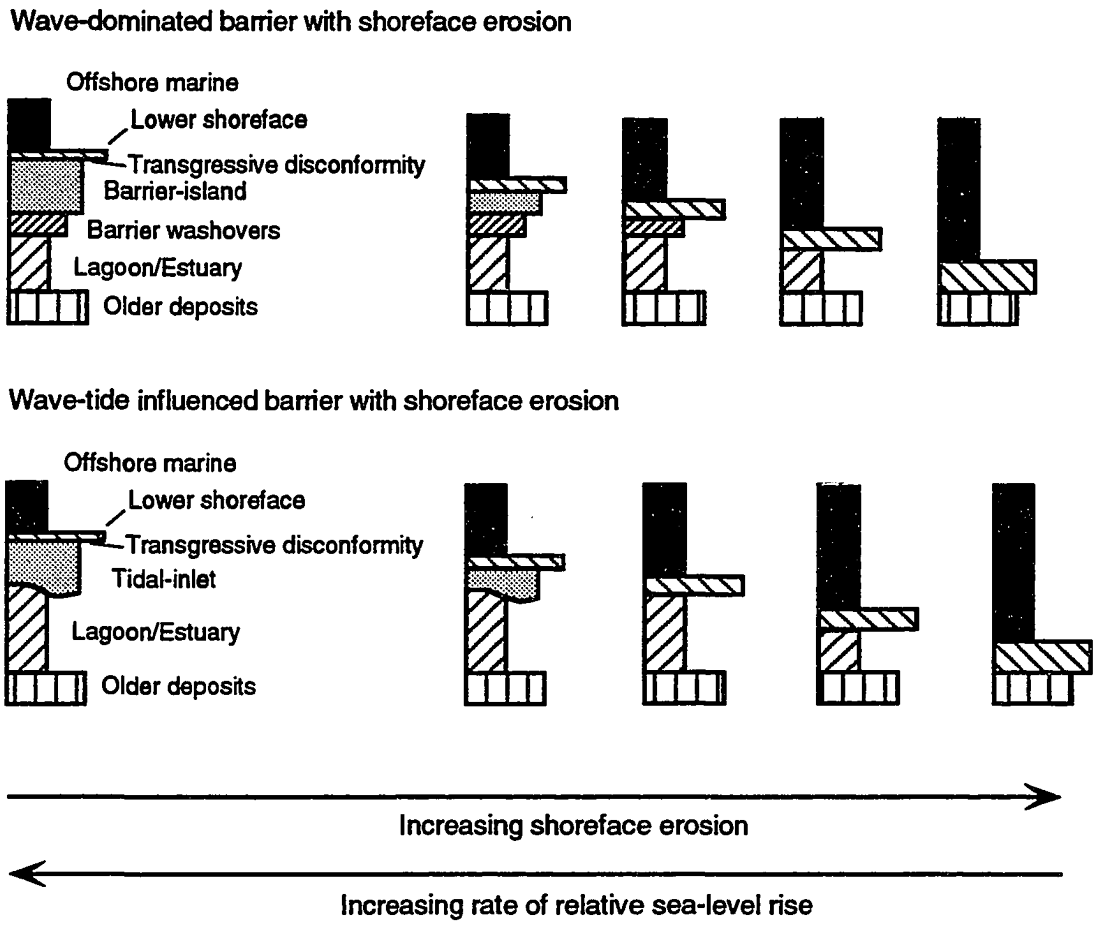

Figure 3-15 - Factors influencing barrier-island preservation. Diagram showing relation between shoreface erosion, rate of relative sea-level rise, and preservation potential for barrier-island successions in wave-dominated and wave-tide influenced settings. Barrier-island successions in the lower Kayak were deposited in a wave-tide incluenced setting. Modified from Heward (1981).

erosion as relative sea level continued rising and the supply of coarse-grained sediment steadily decreased.

As sea-level continued rising, barrier islands were initially able to retrograde and keep pace with the rise because of a readily available supply of coarse-grained sediment from reworked fluvial deposits and longshore currents along open stretches of the coast. During this initial phase, barrier islands migrated landward (northward) through a combination of storm-washover and shoreface-retreat processes in a manner analogous to Holocene barriers along the Delaware coast (Kraft, 1971; Kraft and John, 1979). This process continued until the supply of sediment was insufficient to maintain the barrier system as underlying fluvial sediment (Kekiktuk Conglomerate) and terrigenous clastic source areas (pre-Middle Devonian rocks) were buried due to continued transgression. Barriers probably responded by getting progressively smaller, until they were ultimately drowned and the surf zone skipped some distance to the north. Regional study of the Endicott Group suggests that barrier islands were probably not re-established at a more northerly position. However, outcrop belts are widely spaced and oriented roughly parallel to the Carboniferous coastline (Figure 3-3), so this cannot be established with certainty.

Tidal-inlet deposits are a prominent feature in the lower Kayak Shale and, at one locality, lateral inlet migration has resulted in complete removal of barrier-island deposits. The presence of tidal inlets and the low abundance of distal storm-washover deposits suggests that tides were in the high microtidal to low mesotidal range (Hayes, 1979). Flood tidal-delta deposits have not been recognized in estuarine deposits of the lower Kayak Shale. Hayes (1979) noted that flood tidal deltas tend to be small or absent along microtidal and low mesotidal coasts. Ebb tidal-delta deposits, if originally present, would be expected to have a low preservation potential in transgressive settings due to their high stratigraphic position (Reinson, 1984).

The stratigraphic position of the lower Kayak Shale above a relatively thin, discontinuous, but extensive fluvial succession associated with low topographic relief (up to 128 m) on the sub-Mississippian unconformity, combined with the widespread distribution of the overlying shallow-marine middle Kayak Shale, suggest deposition related to relatively minor subsidence of continental crust rather than deposition at the basin margin or, in a basinal setting, over thinned continental or oceanic crust. This is consistent with deposition on the landward side of a tectonic hinge zone along a subsiding passive continental margin.

CONCLUSIONS

1. Seven lithofacies have been recognized in the lower Kayak Shale that record deposition in barrier-island, tidal-inlet, and back-barrier environments.

2. The association between the lower Kayak Shale and thick, underlying valley-fill fluvial successions of the Kekiktuk Conglomerate suggests that the distribution of the lower Kayak was controlled by paleotopographic relief on the sub-Mississippian unconformity, and that the lower Kayak Shale records deposition in an estuarine system.

3. Barrier-island and associated tidal-inlet environments migrated landward (north) by a process of shoreface erosion and concomitant redistribution of sediment landward into the estuarine setting as storm-generated washovers.

4. The steadily decreasing supply of coarse-grained detritus to the barrier-island system, combined with a steady rise in relative sea-level, ultimately led to drowning and shutdown of marginal-marine depositional systems and establishment of shallow-marine conditions.

5. The degree of preservation of barrier-island and tidal-inlet deposits in the lower Kayak Shale suggest deposition in incised paleovalleys and, possibly, a high rate of relative sea-level rise.

6. The stratigraphic position of the lower Kayak Shale above thin, discontinuous but extensive valley-filling fluvial deposits of the Kekiktuk Conglomerate and below shallow-marine deposits of the middle Kayak Shale suggest deposition landward of the tectonic hinge zone along a subsiding passive continental margin.

CHAPTER 4: TERRIGENOUS CLASTIC-TO-CARBONATE TRANSITION: DEPOSITION OF THE UPPER KAYAK SHALE

Diverse terrigenous clastic and carbonate rocks of the Ellesmerian sequence (Figure 4-1) in northern Alaska were deposited on a south-facing passive continental margin from Early Carboniferous to Early Cretaceous time (Bird and Molenaar, 1987). The base of the Ellesmerian sequence consists of the Kekiktuk Conglomerate and Kayak Shale of the Endicott Group (Figure 4-2), a widespread transgressive succession whose regional distribution records increasing accomodation and distance from terrigenous clastic source areas due to relative sea- level rise. The Endicott Group is situated above a regional unconformity, referred to herein as the sub-Carboniferous unconformity, that represents a hiatus of at least 35 Ma (DNAG time scale - Lower Devonian below and latest Tournaisian-earliest Visean above; Blodgett et al., 1991; Utting, 1990, 1991a,1991b). The sub-Carboniferous unconformity most likely records a transition from dominantly contractional tectonics below to extensional tectonics above, followed by thermally controlled subsidence (Anderson and Wallace, 1991; Moore et al., 1992).

The Carboniferous Endicott Group in the northeastern Brooks Range is a well-exposed example of a post-rift transgressive succession that was deposited landward of a tectonic hinge zone, over a rift-flank unconformity. The fluvial Kekiktuk Conglomerate records deposition in incised paleovalleys in response to relative sea-level rise and regional transgression. As transgression continued, fluvial dispersal systems were drowned and

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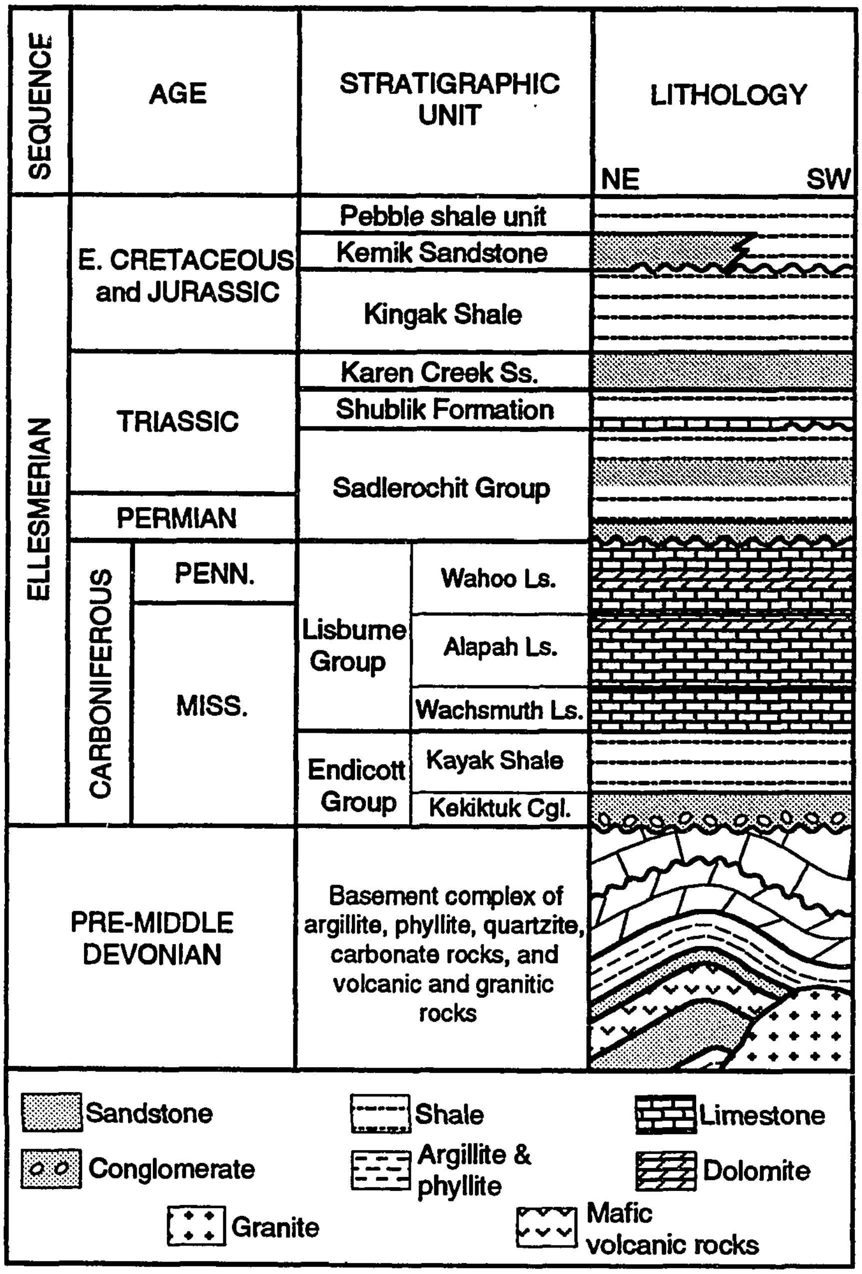


Figure 4-1 - Generalized column of the Ellesmerian sequence in the northeastern Brooks Range. No scale intended. Modified from Bader and Bird (1986).

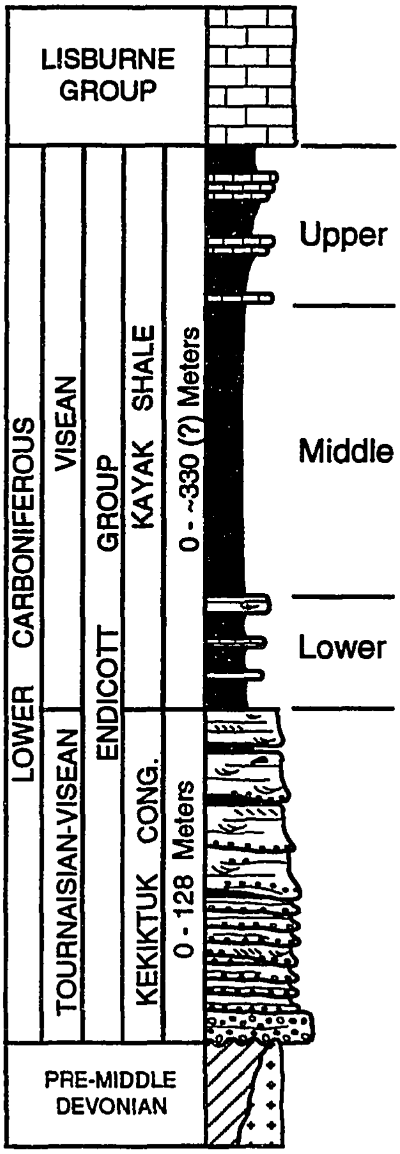


Figure 4-2 - Generalized column of the Endicott Group in the northeastern Brooks Range. No scale intended.

gradually replaced by marginal- and shallow-marine environments with anaerobic to dysaerobic conditions recorded in the Kayak Shale.

The transition upward and basinward (toward the south) from terrigenous clastic-dominated environments to platform carbonate rocks recorded in the Endicott and Lisburne Groups, respectively, is a commonly recognized trend in passive continental margin successions from North America and elsewhere (Aitken, 1978; Belperia, 1983; Bond et al., 1989; Chow and James, 1987; Davies et al., 1989; James et al., 1989; and Read, 1989). Despite this common stratigraphic trend, few detailed studies have been published of terrigenous clastic-to-carbonate transitions deposited during the early drift phase of passive continental margin evolution. Most published studies focus on transitions later in the evolutionary cycle of passive continental margins (e.g. Markello and Read, 1982) or from other tectonic settings (e.g. Dorobek and Read, 1986; Handford, 1986; Read, 1980; Walker et al., 1983).

The uppermost beds of the Kayak Shale form a well-exposed gradational transition between terrigenous clastic-dominated environments below and shallow-water carbonate environments recorded in the Lisburne Group above. The upper beds of the Kayak Shale consist of a broad suite of cyclic and acyclic mixed terrigenous clastic and carbonate rocks that record deposition within a shallow-marine setting dominated by anaerobic to dysaerobic conditions, but in which well-oxygenated conditions developed locally. In this paper, we present a systematic description of the organization of the upper Kayak Shale in the northeastern Brooks Range and relate its organization to paleogeography and variations in the supply of terrigenous clastic sediment. We conclude with a reconstruction of the depositional setting and a discussion of the factors that controlled the terrigenous clastic-to-carbonate transition in the northeastern Brooks Range.

REGIONAL GEOLOGIC SETTING

In northern Alaska, a regional sub-Carboniferous angular unconformity has been recognized throughout the North Slope subsurface and at widely spaced locations across the Brooks Range that truncates rocks as young as Early Devonian (Blodgett et al., 1991) and represents a fundamental change from dominantly contractional deformation below to extensional deformation above (Moore et al., 1992). In the northeastern Brooks Range, the Carboniferous Endicott Group rests above this unconformity and consists, in ascending order, of fluvial and marginal-marine terrigenous clastic rocks of the Kekiktuk Conglomerate and marginal- to shallow-marine terrigenous clastic and carbonate rocks of the Kayak Shale (Figure 4-2). The Endicott Group is latest Tournaisian to late Visean in age (Armstrong and Mamet, 1977; Utting, 1990, 1991a, 1991b), and forms the base of a northward-onlapping succession (Brosge et al., 1962; Nilsen, 1981) of terrigenous clastic and carbonate strata assigned to the Ellesmerian sequence (Figure 4-1).

In the Continental Divide region of the eastern Brooks Range, the Carboniferous Endicott Group is slightly older (Tournaisian to Visean) and is situated unconformably above a thick Middle to Upper (?) Devonian terrigenous clastic succession (Anderson et al., 1992). The Devonian and Lower Carboniferous successions have been interpreted to record the rift and subsequent early drift phases, respectively, in the formation of a passive continental margin by Anderson and Wallace (1991) and Anderson et al. (1992). Farther south of the Continental Divide in the eastern Brooks Range, and throughout the central and western Brooks Range, a stack of south-derived allochthons contain Upper Devonian through Lower Cretaceous rocks (Mull, 1982; Moore et al., 1992). The structurally lowest allochthon, referred to as the Endicott Mountains allochthon (Mull, 1982), contains a thick Upper Devonian to Lower Carboniferous clastic wedge that consists of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale (Moore et al., 1992). This wedge records progradation to the south and southwest of major fluvial-deltaic depocenters that formed along the Late Devonian-Early Carboniferous basin margin (Moore and Nilsen, 1984; Moore et al., 1992). Middle and Upper Devonian terrigenous clastic rocks are missing in the northeastern Brooks Range.

These regional relations suggest that Middle Devonian to Lower Carboniferous strata in the Brooks Range are part of a southward-thickening and -deepening sedimentary wedge that was constructed during the rift and early drift phases in the evolution of a passive continental margin (Anderson and Wallace, 1991; Anderson et al., 1992; Moore et al., 1992). Further evidence of Devonian rifting is provided by common and widespread bimodal volcanic rocks interbedded within Devonian sedimentary rocks in the southern Brooks Range (Dillon et al., 1987; Dillon, 1989; Moore et al., 1992).

In the northeastern Brooks Range, the Kekiktuk Conglomerate is thickest (up to 128 m) in incised paleovalleys and progressively thins toward, and eventually pinches out against, adjacent paleotopographic highs (LePain and Crowder, 1992). These relationships indicate that where the Kekiktuk Conglomerate is thickest, fluvial systems were confined within incised paleovalleys cut into pre-Middle Devonian rocks and, where only a thin veneer of Kekiktuk is present, it records deposition along the flanks of paleotopographic highs on the sub-Mississippian unconformity (LePain and Crowder, 1992b).

Slow post-rift subsidence of continental crust landward of the hinge zone (e.g. Braun and Beaumont, 1989), combined with eustatic sea-level rise throughout Early Carboniferous time (Hallam, 1984) resulted in regional transgression, flooding of fluvial dispersal systems, and establishment of a broad suite of marginal- and shallow-marine depositional environments recorded in the Kayak Shale. As transgression continued, estuarine conditions developed above valley-filling fluvial and marginal-marine successions of the Kekiktuk Conglomerate. Local paleotopographic highs were onlapped and buried beneath a veneer of marginal-marine mud of the Kayak Shale.

The Kayak Shale onlaps and pinches out above a regional paleotopographic high in the Sadlerochit Mountains (Figure 4-3). The Sadlerochit high was transgressed and buried beneath shallow-water carbonate rocks of the Lisburne Group by late Visean time (zone 16i, earliest Chesterian; Armstrong, 1974). The Kayak Shale is absent and thin, discontinuous successions of the Kekiktuk Conglomerateor rocks of the Lisburne Group rest nonconformably on the Devonian Okpilak batholith around its margins. These indicate that this feature also was a paleotopographic high throughout much of the Visean. Armstrong (1974) and Armstrong and Bird (1974) extended the Sadlerochit high eastward, north of Leffingwell Ridge, to the Canadian border on the basis of foram biostratigraphy of the Lisburne Group. Along Leffingwell Ridge, the Kekiktuk Conglomerate is thin and discontinuous and the Kayak Shale is continuous forming successions up to 285 m thick.

Paleogeographic reconstructions for Carboniferous strata in the northeastern Brooks Range show fluvial and marginal-marine sand of the Kekiktuk Conglomerate to the north and carbonate sediments of the Lisburne Group to the south (Armstrong, 1974; Armstrong and Bird, 1974). Between these areas, terrigenous mud and argillaceous carbonate sediment of the Kayak Shale accumulated under open- to restricted-marine conditions. These regional relations, combined with the limited thickness, widespread distribution, and stratigraphic position of the Kekiktuk Conglomerate below the marginal- and shallow-marine Kayak Shale, strongly suggest that the Carboniferous Endicott Group in the northeastern Brooks Range records deposition in a south-sloping upland area, probably situated landward of the tectonic hinge zone along a subsiding passive continental margin. Subsidence, possibly combined

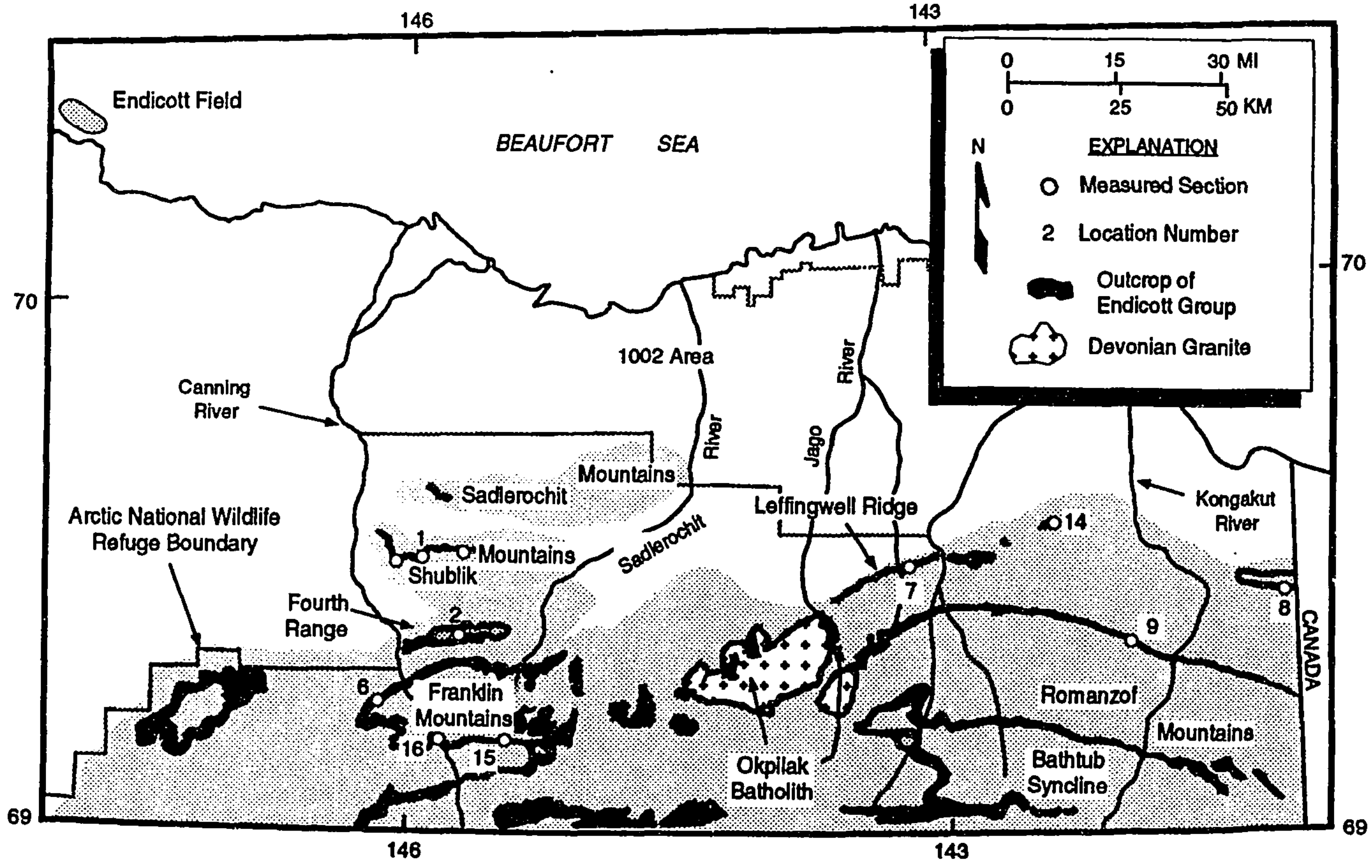


Figure 4-3 - Map of northeastern Brooks Range. Map shows outcrop pattern for the Endicott Group and location of measured sections. Numbers refer to locations discussed in chaper 4. Modified from Bird et al. (1987).

with eustatic sea-level rise (e.g. Hallam, 1984), resulted in northward retreat of terrigenous clastic source areas, flooding of the low-relief rift-flank region, and ultimate establishment of an extensive shallow-water carbonate ramp (Lisburne Group).

In the northeastern Brooks Range, Cenozoic contractional deformation has resulted in several east-west trending anticlinoria (Wallace and Hanks, 1990). The Kayak Shale and associated strata crop out along the flanks of these anticlinoria (Figure 4-3).

ORGANIZATION OF THE KAYAK SHALE

Bowsher and Dutro (1957) named the Kayak Shale for ~290 m of Lower Carboniferous marine black and dark gray shale, siltstone, sandstone, and argillaceous limestone that is exposed in the central Brooks. At its type locality, the Kayak is Tournaisian in age (Armstrong and Mamet, 1977), and is situated disconformably above the Upper Devonian-Lower Carboniferous Kanayut Conglomerate and disconformably below the Lisburne Group (Bowsher and Dutro (1957). Bowsher and Dutro (1957) recognized five informal members in the Kayak Shale including, in ascending order, a basal sandstone, lower black shale, argillaceous limestone, upper black shale, and a red limestone. Brosge et al. (1962), while working on the Paleozoic sequence in the eastern Brooks Range, recognized a similar black shale succession below the Lisburne Group in exposures east of the Canning River. They considered it to be of Lower Carboniferous age, and referred to it as the Kayak (?) Shale. Following current stratigraphic terminology, we refer to this succession as the Kayak Shale.

We have divided the Kayak Shale into three informal members based on lithology and their relationship to the sub-Carboniferous unconformity, the Kekiktuk Conglomerate, and the overlying Lisburne Group (Figure 4-2). The lower Kayak Shale has been recognized at only a few locations in the northeastern Brooks Range and is restricted to positions above thick, mud-rich, valley-filling fluvial to marginal-marine successions of the Kekiktuk Conglomerate. The contact between the lower Kayak Shale and the underlying Kekiktuk Conglomerate is typically poorly exposed, but appears to be gradational. The lower Kayak Shale consists predominantly of organic-rich mudstone, quartzose sandstone, quartzose bioclastic limestone, and minor anthracitic coal.

The middle Kayak Shale is present throughout the northeastern Brooks Range where a variety of contact relationships have been observed with underlying rocks. The contact between the lower and middle Kayak Shale is sharp. Where the lower Kayak Shale is absent, both sharp and gradational contacts have been observed between the middle Kayak and the underlying Kekiktuk Conglomerate. Where the Kekiktuk Conglomerate is absent above paleotopographic highs, the middle Kayak Shale rests unconformably on pre-Middle Devonian rocks. The middle Kayak Shale consists predominantly of black, dark gray, and locally red-weathering shale. Minor anthracitic coal and sharp-based sandstone beds and bedsets are present locally near the base of the middle Kayak.

The contact between the middle and upper Kayak Shale is gradational. The upper Kayak consists of dark gray to black, organic-rich shale and a variety of carbonate lithologies. The upper Kayak Shale records the transition from terrigenous clastic-dominated environments of the Endicott Group to carbonate-dominated environments of the overlying Lisburne Group.

Mull and Mangus (1972) named a succession of redbeds that consist of calcareous mudstone, sandstone, conglomerate, and silty/sandy carbonate rocks immediately below the Lisburne Group the Itkilyariak Formation and assigned it to the Endicott Group. Redbeds below the Lisburne were first recognized in the central North Slope subsurface, where they form successions up to 120 m thick. Outcrop equivalents were subsequently recognized in the northeastern Brooks Range (Mull and Mangus, 1972). However, the formation in outcrop differs significantly from its subsurface counterpart. In the subsurface, the Itkilyariak Formation is dominated by terrigenous clastic rocks (up to 95%), whereas, the stratigraphic equivalent in outcrop is only locally red-weathering and generally dominated by argillaceous and silty/sandy carbonate lithologies. Terrigenous clastic interbeds are present locally, but form a relatively minor component (LePain and Crowder, 1991). Laterally discontinuous red-weathering calcareous sandstone, conglomerate, and mudstone successions up to 5 m thick are present in the northeastern Sadlerochit Mountains, where they rest unconformably on pre-Middle Devonian rocks in localized paleotopographic depressions (LePain and Crowder, 1991). These rocks are not a mappable unit and are probably a basal facies of the Lisburne Group. Elsewhere in the northeastern Brooks Range, we assign argillaceous and silty/sandy carbonate rocks below the Lisburne Group to the Kayak Shale.

LITHOFACIES

We recognize eight lithofacies in the upper Kayak Shale. This section presents brief descriptions and interpretations for each lithofacies, which are also summarized in Table 4-1. We use Wilson's (1975) standard facies belts for our environmental interpretations. The following section discusses lateral and vertical lithofacies relations.

Black Shale

This lithofacies consists of fissile, organic-rich clay shale. Locally, quartz silt is present in millimeter-scale laminae. Shale is locally calcareous and pyritic, and rare disc-shaped pyritic siltstone concretions have been observed. Total organic carbon content ranges from 0.8 to 7.9 wt. %. Palynologic samples collected from black shales have yielded a diverse land-

Table 4-1 - Summary descriptions of lithofacies in the upper Kayak Shale.

LITHOFACIES	ALLOCHEMS	TERRIGENOUS CLASTIC GRAINS	ORTHOCHEMS	SED./BIOGENIC STRUCTURES	ENVIRONMENT
Black Shale	Rare pelmatozoans, gastropods, and small (<2 cm long) horn corals.	Clay- and minor silt-sized grains, + abund. woody and coaly plant fragments (TOC 0.8 to 7.9 wt. %).	Locally abundant pyrite and calcite.	Bioturb. is absent or very low.	Low-energy, anaerobic marine setting.
Dolomitic Ss.	Rare silic. sponge spicules, ostracods, abraded pelmats., bryozoans, and brachiopods.	Quartz, minor chert, silt- to coarse sand-size, poor to moderately sorted. Argillac. material locally abundant.	Ferrug. dolomite anhedra (15 to 30%, locally up to 60% of rock). Rare euhedral plagioclase.	Moderate bioturb. to burrow-mottled; *Zoophycos* common.	Episodic sedimentation in dysaerobic setting.
Fossiliferous Ss.	Common abraded pelmats., bryozoans, and undif. coral frags.	Quartz, minor chert, silt- to coarse sand-size, moderate to well-sorted.	Euhedral to anhedral dolomite (generally 5 to 20% of rock, complete dolomtization locally).	Common wave-ripple cross-lamination.	Open-platform setting, above fairweather wave-base.
Pelmatozoan Lime Mst./Wkst.	Pelmats. and bryozoans, with subordinant ostracods, coral frags., forams, algae, bivalves, calcispheres, trilobites, and gastropods. Grains micritized.	Argillac. material and silt- and sand-sized quartz common (up to 30% locally).	Euhedral to anhedral dolomite (up to 40%, complete dolomtization locally).	Highly bioturb. to burrow-mottled. Common shale drapes.	Open-platform setting, below fairweather wave-base.
Pelmatozoan Pkst./Gst.	Pelmats. and bryozoans, with subordinant ostracods, coral frags., forams, algae, bivalves, calcispheres, trilobites, and gastropods. Grains micritized.	Argillac. material common in pkst., silt- and sand-sized quartz common (up to 30% locally).	Euhedral to anhedral dolomite common (up to 30%).	Pkst. highly bioturb. to burrow-mottled; shale drapes common in pkst.; common planar cross-beds (sets up to 0.7 m) in gst.	Open-platform setting, skeletal sand shoals deposited above fairweather wave-base.
Spiculitic Wkst./Pkst.	Silic. sponge spicules and peloids, with subordinant ostracods, pelmats., bryozoans, brachiopods, calcispheres, forams, algae, and coral frags present locally.	Common argillac. material (up to 15%).	Euhedral to anhedral dolomite common (up to 40%, completely dolomitized locally); pyrite is widespread, but <1 to 2% of rock. Black chert nodules common.	Low to high bioturb., locally burrow-mottled.	Restricted- to marginally restricted-platform setting, marginally dysaerobic, below fairweather wave-base.
Dolomudstone	Rare silic. sponge spicules, peloids, ostracods, and brachiopods present locally.	Common argillac. material (up to 20%) and silt-sand-sized quartz (up to 15%).	Abund. crystalline dolomite, eudderal to anhedral crystals <0.02 to 0.05 mm.	Rare horizontal traces on bed surfaces; well-preserved alternating lamina of argillac. dolomite and dolomite, silty/sandy dolomite lamina common locally; locally abund. dolomite intraclasts.	Restricted-platform setting, tidal flat.
Coralline/Algal Boundstone	*Syringipora* and *Lithostrotionella* coral, with rare algal boundstone (*Stachelinids* and undif. alga); pelmat. wkst. and pkst. fill space between septa.	Common argillac. material (up to 20%) between septa, silt- and sand-sized quartz present locally between spota.	Euhedral to anhedral dolomite crystal 0.05 to 0.5 mm and chalcedonic chert replacing septa (up to 50% locally).	?	Marginally restricted- to open-platform setting, below or near fairweather wave-base, turbid water.

derived palynoflora, abundant woody and coaly plant fragments, and locally contain scolecodonts (Utting, 1990, 1991a, 1991b). Millimeter-scale laminae are present locally, are well-preserved, and do not appear bioturbated.

The black shale lithofacies was deposited in an anaerobic to dysaerobic, marine setting where substantial volumes of fine-grained terrigenous detritus, including plant material, was delivered from adjacent terrestrial environments. Anaerobic conditions are required to prevent the breakdown of dead organic matter by benthic metazoans and bacteria, and hence are essential for preservation of organic matter in sediments (Allen and Allen, 1990; Potter et al., 1980). Abundant angular woody and coaly fragments also indicate an organic-rich sediment deposited in close proximity to the coastline. The lack of bioturbation suggests deposition in an anaerobic to dysaerobic setting. In these settings the benthos is sparse or non-existent (Ekdale and Mason, 1988; O'Brien and Slatt, 1990).

Dolomitic Sandstone

This lithofacies consists of orange-brown weathering sandstone laminae and beds. Laminae are lenticular and 0.2 to 2.0 cm thick. Beds are 2 to 10 cm thick, range from wavy-discontinuous to even-parallel and laterally continuous geometri.es, and locally form coarsening- and thickening-upward successions. Where the degree of bioturbation is low, sandstone beds commonly contain wave-ripple cross-laminae in sets up to 5 cm thick. Siliciclastic material consists of poorly to moderately sorted, angular-to-subround, silt- to coarse sand-sized (0.04 to 0.6 mm) quartz and minor chert (Figure 4-4). Discontinuous shale drapes (shale flasers) up to 2 cm thick are common between sandstone beds. Dolomite content ranges from 15 to 30%, however, beds consisting of up to 60% dolomite are locally present. Dolomite crystals are generally anhedral and ferruginous and range from 0.06 to 0.7 mm in

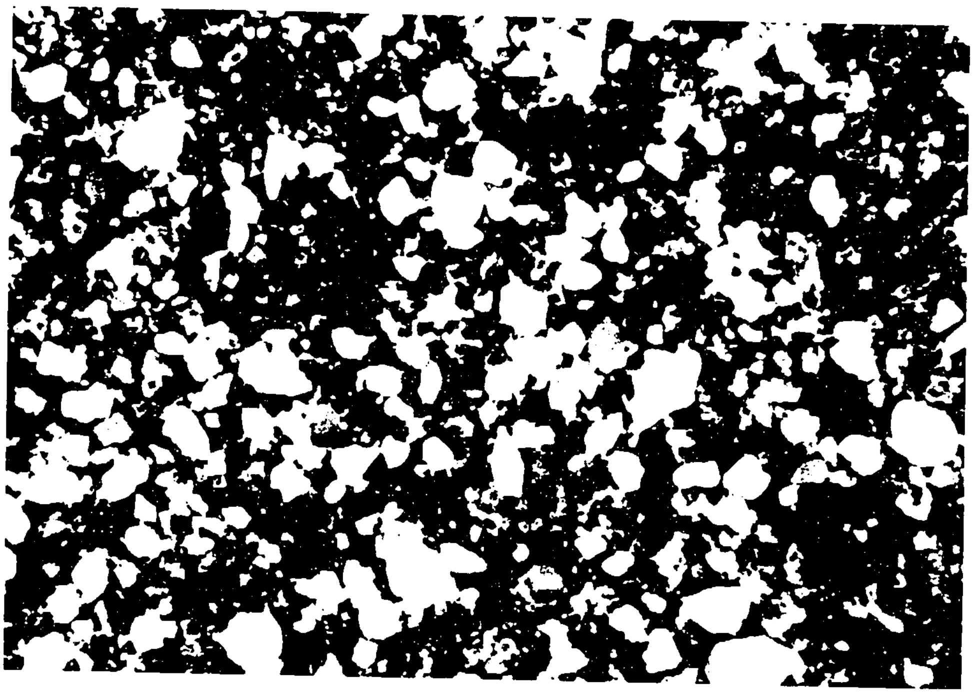


Figure 4-4 - Photomicrograph of dolomitic sandstone lithofacies. Scale is 1 cm = 0.43 mm.

size. Euheral dolomite rhombs are locally present. Argillaceous material is present throughout, but is most abundant in disrupted lenticular laminae <2 mm thick.

Sandstone is moderately to highly bioturbated, and the uppermost 5 to 20 cm of some dolomitic sandstone successions are completely burrow-mottled, highly argillaceous, and characterized by distinctive flaggy to slabby parting. Overall, the degree of bioturbation is greatest in successions with abundant argillaceous material. Most trace fossils are of uncertain affinity (possible *Planolites*; e.g. Benyon and Pemberton, 1992; Hantzschel, 1975; Pemberton et al., 1992), however, the top surface of some beds has a distinctive, circular structure up to 1.0 m in diameter that resembles coiled rope. These resemble Paleozoic forms of the deposit feeder *Zoophycos* (Frey and Pemberton,1984). Skeletal grains are absent in most beds, but can comprise up to ~5% of the rock locally and consist of siliceous sponge spicules, thin-walled ostracods, and abraded pelmatozoans, fenestrate bryozoans, and brachiopods. Scattered impressions of bivalves are present locally on bedding surfaces.

The depositional setting for the dolomitic sandstone lithofacies is difficult to interpret due to bioturbation and pervasive dolomitization. However, the features described above suggest deposition in a restricted-platform setting below fairweather wave-base, where coarse-grained sediment was transported on to a muddy shelf by storm-generated flows (e.g. Aigner, 1985; Johnson and Baldwin, 1986). Shale drapes and the degree of bioturbation suggest that deposition was episodic with intervening low-energy intervals long enough to allow for shale deposition, substrate colonization, and associated moderate to complete sediment disruption by deposit-feeding organisms (Aigner, 1985; Howard, 1975). The general absence of skeletal grains in most beds and common *Zoophycos* burrows indicate deposition in a restricted, dysaerobic setting. Dysaerobic settings generally support sparse communiti.es of soft-bodied deposit feeders and lack a shelly benthos (Ekdale and Mason, 1988). *Zoophycos* have been reported from a wide variety of environments, ranging from bathyal to intertidal, but are usually associated with restricted, oxygen-deficient, dysaerobic settings (Ekdale and Mason, 1988; Miller and Johnson, 1981; Frey and Pemberton, 1984; Seilacher, 1967). Dolomite is diagenetic and probably replaced an original lime mud precursor that supported a sparse, limited fauna of sponges and ostracods. Lime mud would have been mixed in with sand as storm-generated flows passed over a muddy substrate. The broken and abraded condition of pelmatozoan and bryozoan grains suggests significant transport.

Fossiliferous Sandstone

This lithofacies consists of light tan-brown weathering sandstone beds up to 10 cm thick. Beds are laterally continuous, even and parallel, and form successions up to 2 m thick. Beds generally contain horizontal laminae 0.5 to 1.5 cm thick, but ripple cross-laminae in sets up to 4 cm thick are locally abundant. Horizontal laminae and sets of ripple cross-laminae are commonly separated by very thin (<2 mm) shale partings. Most sets of ripple cross-laminae have complex relations with surrounding sets and foreset laminae in adjacent sets are commonly opposed. Multiple sets of cross-laminae with uniformly dipping foresets are present locally. Siliciclastic material consists of moderately to well-sorted, angular to subround, silt- to coarse sand-sized (0.04 to 0.6 mm) quartz and minor chert. Argillaceous material is generally rare but, where present, is concentrated in thin (<1.0 mm), discontinuous laminae. Dolomite content ranges from 5 to 20%; crystals are generally anhedral, and range from 0.06 to 0.7 mm in size. Euheral dolomite rhombs are locally present. Skeletal grains are ubiquitous and account for up to 15% of the total rock. Broken and abraded pelmatozoans and bryozoans dominate, but undifferentiated coral fragments, disarticulated brachiopods, foraminifera, and algal grains of uncertain affinity have also been recognized.

The fossiliferous sandstone lithofacies was deposited in shallow-water,open-platform settings, above fairweather wave-base. Transport of sand to shallow, open-platform settings was probably accomplished by storm-generated flows (e.g. Aigner, 1985; Kreisa and Bambach, 1982; Walker, 1984). The composition of skeletal grains indicates deposition in marine settings with good circulation and normal marine salinity (Flugel, 1982; Heckel, 1972; Wilson and Jordan, 1983). Sets of cross-laminae with opposed foresets and complex lateral and vertical relations between adjacent sets are abundant and similar to wave-ripple cross-laminae described from Lower Carboniferous shallow-marine successions in Ireland (Raaf et al., 1977). This suggests that sand was deposited above fairweather wave-base and subsequently reworked by shoaling waves. Depending on the hydrodynamic setting of the environment - open or protected - the depth to fairweather wave-base would have been somewhere between 4 and 20 m (Flugel, 1982). Relatively uncommon ripple cross-laminae with uniformly dipping foreset laminae between sets suggest episodic unidirectional transport, possibly by storm-generated flows (e.g. Aigner, 1985). Structures specifically attributable to storms (i.e. tempestite sequences; Aigner, 1985; Kreisa and Bambach, 1982) have not been observed. However, the paucity of current-ripple structures and abundance of wave-ripple cross-laminae suggest deposition above fairweather wave-base, where sediment reworking by shoaling fairweather waves would destroy most of the depositional record of storms (Elliot, 1986b; Leckie and Walker, 1982; Walker, 1984).

Pelmatozoan Lime Mudstone/Wackestone

This lithofacies consists of lime mudstone and wackestone beds that weather gray, dark gray, and dark maroon. Beds are 0.04 to 0.5 m thick, appear broadly lenticular in outcrop, and commonly form upward-thickening successions in which lateral bed continuity increases gradually upsection. Lime mudstone and wackestone are commonly argillaceous. Clay-, silt-, and sand-sized material constitutes up to 30% of this lithofacies locally; it is generally scattered throughout beds, but is locally concentrated in discontinuous, millimeter-scale laminae. Discontinuous shale drapes up to 1 cm thick are common between beds. Skeletal grains consist mainly of pelmatozoans and bryozoans (fenestrate and ramose forms; Figure 4-5). Subordinate skeletal grains include, in approximate order of decreasing abundance, ostracods, coral fragments, foraminifera, algae, bivalves, calcispheres, trilobites, and gastropods. Grain boundaries are commonly micritized and, rarely, contain visible micro-borings filled with lime mudstone. Most algal grains are of uncertain affinity, but *Stacheiinids* have been identified locally, and fragments of *Lithostrotionella* and *Syringipora* corals have been identified. The degree of bioturbation varies from moderate to complete burrow-mottling. Individual burrow structures, where visible, are filled with argillaceous and quartzose skeletal lime mudstone, wackestone, and locally packstone.

The pelmatozoan lime mudstone/wackestone lithofacies was deposited in a subtidal, low-energy open-platform setting. The skeletal grain association is typical of warm- water environments with normal marine salinity levels (Flugel, 1982; Heckel, 1972; Wilson, 1975; Wilson and Jordan, 1983). The high lime mud content indicates minimal winnowing by shoaling waves and deposition below fairweather wave-base (e.g. Wilson and Jordan, 1983). However, micrite envelopes are common and are typical of shallow-water (<25 m) carbonate environments (Perkins and Halsey, 1971). Clay-, silt-, and sand-sized siliciclastic grains are generally scattered throughout beds, however, they form coherent laminae and shale drapes locally and commonly form part of the fill for burrow structures. This suggests that siliciclastic sediment was introduced to the open-platform setting periodically, possibly associated with storms, and then reworked by burrowing organisms.

Figure 4-5 - Photomicrograph of pelmatozoan lime mudstone/wackestone lithofacies. Note large pelmatozoan grain in upper left of photograph. Scale is 1 cm = 0.34 mm.

Pelmatozoan Packstone/Grainstone

This lithofacies consists of packstone and grainstone beds that weather gray, dark gray, and maroon. Beds are 0.1 to 1.0 m thick, appear broadly lenticular in outcrop, and have sharp, locally erosive contacts. Grainstone beds commonly thicken along local strike, appear channelized locally, and contain planar-tabular and -tangential cross-beds up to 0.7 m thick. Packstone beds are commonly bioturbated and argillaceous, and clay-sized material is generally scattered throughout or, rarely, is concentrated in discontinuous, millimeter-scale laminae. Discontinuous shale drapes up to 3 cm thick are common between packstone beds. Silt- and sand-sized quartz grains are common in packstone and grainstone, and beds locally contain up to 30% detrital quartz. Silt- and sand-sized siliciclastic grains are generally scattered throughout beds. However, well-segregated laminae of sandy grainstone and grainstone are present locally, where they define sets of ripple cross-laminae up to 5 cm thick. Most sets of cross-laminae have complex relations with surrounding sets and foreset laminae in adjacent sets are commonly opposed.

Pelmatozoans and bryozoans dominate the skeletal grain population (Figure 4-6). Subordinant skeletal grains are similar to those recognized in the pelmatozoan lime mudstone/wackestone lithofacies, including *Stacheiinid* alga and *Lithostrotionella* and *Syringipora* coral fragments. *Stacheiinids* and *Syringipora* are the most common forms of algae and coral fragments, respectively. Skeletal grain margins are commonly micritized. Grain abrasion is moderate.

The pelmatozoan packstone/grainstone lithofacies was deposited above fairweather wave-base in an open-platform setting as skeletal shoals. Ripple cross-laminae are similar to wave-ripple cross-laminae described from Carboniferous shallow-marine successions by Raaf

Figure 4-6 - Photomicrograph of pelmatozoan packstone/grainstone lithofacies. Scale is 1 cm = 0.28 mm.

et al. (1977). Grainstones form in relatively high-energy settings (Wilson, 1975), and commonly aggrade to intertidal depths. Scoffin (1987) observed that skeletal sand shoals typically develop at depths of 0 to 5 m. The channelized geometry and common large-scale cross-bedding suggest deposition in channels that cut across skeletal shoals in some places (cf. Scoffin, 1987). Bimodal sorting characteristic of packstone indicates incomplete winnowing of mud, possibly on the deeper parts of shoals.

Spiculitic Wackestone/Packstone

This lithofacies consists of wackestone, packstone, and minor lime mudstone that weather gray, dark gray, dark brown, and locally maroon. Beds are 5 to 30 cm thick and irregular but continuous along local strike. Sponge spicules are 0.08 to 0.25 mm in diameter and consist predominantly of monaxial siliceous forms (Figure 4-7), although calcareous forms are locally present. Peloids are commonly present, locally approach spicules in abundance, and range from 0.05 to 2.0 mm in apparent diameter. Subordinate skeletal grains include ostracods, pelmatozoans, bryozoans, brachiopods, calcispheres, foraminifera, algae, and coral fragments. Dark gray and black bed-parallel chert nodules are abundant, form 10 to 70% of beds, and range from a few centimeters to over 1.0 m in length. Argillaceous material is ubiquitous, forms up to 15% of the rock, and is generally dispersed throughout beds, however, discontinuous shale drapes up to 0.5 cm thick are common. Bioturbation varies from low to high and biogenic traces are of uncertain affinity. In burrow-mottled beds, discontinuous burrow structures are commonly filled with dark gray clay-rich wackestone and packstone. Wackestone and packstone contain up to 40% dolomite. Completely dolomitized beds have been observed locally, but are rare. Dolomite crystals are anhedral to euhedral and range from 0.03 to 0.2 mm across. Pyrite is widespread and generally forms <1 to 2% of the rock.

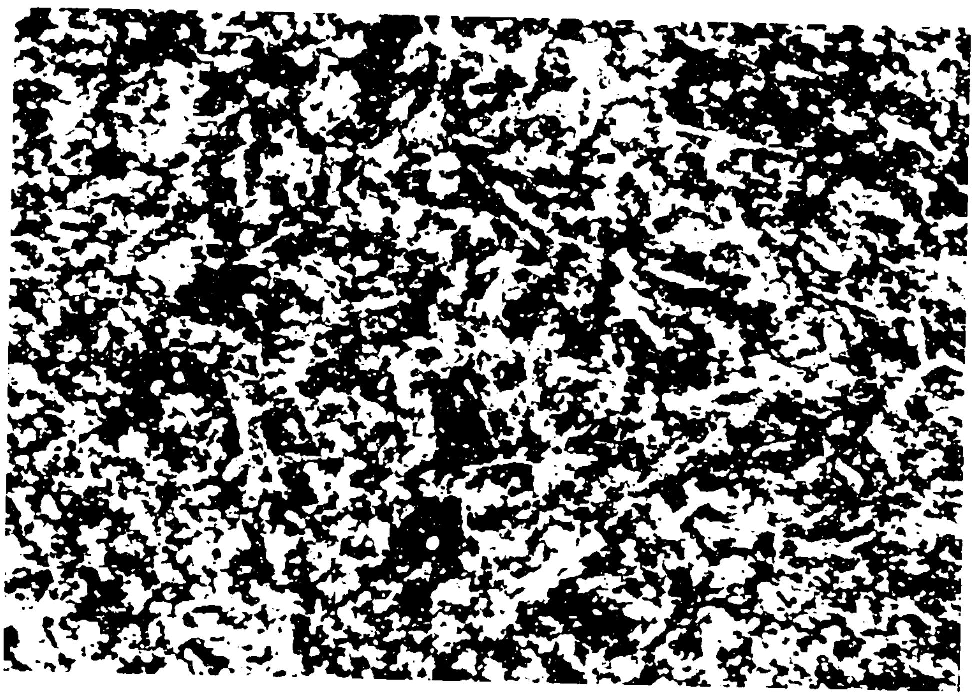


Figure 4-7 - Photomicrograph of spiculitic wackestone/packstone lithofacies. Spicules are monaxial and siliceous. Note burrow-mottled texture and abundant argillaceous material (black areas). Scale is 1 cm = 0.28 mm.

The spiculitic wackestone/packstone lithofacies was deposited in restricted-platform settings, below fairweather wave-base, as muddy buildups. Spiculitic lithologies are generally associated with low-energy deep-water settings (Wilson, 1975), however, Caravoc and Ferm (1968) and Lane (1981) have described spiculites from marginal- and shallow-marine successions in the Appalachian and Illinois basins, respectively. Also, Armstrong (1974) and Gruzlovic (1991) have described spiculitic wackestone and packstone successions in the overlying Lisburne Group and suggest deposition in low-energy restricted-platform settings. The common association between spicules and peloids in this lithofacies suggests deposition in a relatively shallow restricted-platform environment. Peloids are most commonly associated with low-energy, warm-water seas with restricted circulation (Scoffin, 1987). Marginally dysaerobic conditions are indicated by the abundance of sponge spicules and argillaceous material, and ubiquitous pyrite. Dark-colored spiculitic limestones and cherts have been interpreted to record deposition in marginally dysaerobic settings by Savoy (1992) and Wilson (1975). Wilson (1975) suggested that slightly reducing, low-oxygen conditions could result from turbid water.

Dolomudstone

This lithofacies consists of light tan to tan-brown dolomudstone. Beds vary from wavy- to even-parallel, are 5 to 25 cm thick, and are laterally continuous at outcrop scale. Dolomite crystals are anhedral to euhedral, very fine grained, and range from <0.02 to 0.05 mm in size. Most crystals have cloudy centers surrounded by clearer rims. Well-preserved, alternating laminae of argillaceous dolomite and dolomite dominate, however, silty/sandy dolomite laminae and unlaminated, massive dolomite are present locally. Dark argillaceous laminae probably contain organic material. Rectangular intraclasts of very fine-grained (<0.03 mm), argillaceous dolomite are locally present (Figure 4-8). They are 0.3 to 7 cm long with rounded corners, oriented parallel to bedding, and supported by a matrix of cleaner, coarser-grained dolomite. Discontinuous shale drapes up to 1.0 cm thick (generally <4 mm) separate some beds. Dark gray and black, bed-parallel chert nodules are common, range from a few centimeters to over 25 cm in length, and commonly preserve millimeter-scale laminae. Voids filled with dolomite and calcite spar and resembling birdseye structures have been observed, but are not common. Skeletal and non-skeletal carbonate grains are conspicuously absent throughout much of the dolomudstone lithofacies. However, a limited fauna is present locally and consists of sponge spicules, peloids, and rare ostracods (articulated and disarticulated forms), and poorly preserved brachiopods (?). Evidence of bioturbation is lacking throughout much of this lithofacies, however, horizontal trace fossils of uncertain affinity are present on bed surfaces locally.

The dolomudstone lithofacies records shallow subtidal, intertidal, and possibly supratidal deposition in carbonate tidal-flat settings. Unequivocal interpretation of this lithofacies is precluded by the absence or low abundance of some features commonly associated with carbonate tidal-flat environments (i.e. mudcracks and other features indicating subaerial exposure, birdseye or fenestral structures, and intraclast conglomerates; Shinn, 1983). Alternating millimeter-scale laminae are similar to cryptalgal laminae described by Aitken (1978) from carbonate tidal-flat successions. Rare birdseye-like structures could represent pseudomorphs after gypsum or anhydrite, or the sparry fill of voids left after dissolution of rare skeletal grains. Local intraclast-bearing dolomudstone most likely represents storm-generated rip-ups, but these are not common and by no means unique to carbonate tidal-flat settings (cf. Kreisa and Bambach, 1982; Shinn, 1983; Wilson, 1975). Pervasive dolomite could record

Figure 4-8 - Photomicrograph of dolomudstone lithofacies. Note clasts of slightly argillaceous dolomudstone in silty dolomudstone. Scale is 1 cm = 1.48 mm.

post-depositional diagenetic transformation that was unrelated to the original depositional setting (e.g. Morrow, 1991).

With these caveats in mind, common alternating laminae of fine-grained argillaceous dolomite and dolomite, uncommon intraclast conglomerate and birdseye structures, and a sparse low-diversity fauna suggest deposition in a restricted-platform, carbonate tidal-flat setting - probably in the upper intertidal and supratidal zone. In late Paleozoic and younger carbonate tidal-flat settings, horizontal lamination is restricted to the upper intertidal and supratidal zones, where few burrowing organisms can survive (Shinn, 1983). The dolomudstone lithofacies closely resembles tidal-flat lithofacies recognized in Cambro-Ordovican strata of the Mohawk Valley-Saratoga Springs region of New York (U.S.A.) by Mazzullo et al. (1978). The northeastern Brooks Range was situated in a humid climatic zone during the Visean (Ravn, 1991, 1991b; Utting, 1990, 1991a, 1991b), which could explain the paucity of many features characteristic of carbonate tidal-flat settings (arid tidal flats; e.g. Shinn, 1983). Alternatively, the dolomudstone succession may record deposition as a lime mud buildup below fairweather wave-base that was subsequently dolomitized during burial diagenesis.

Coralline/Algal Boundstone

This lithofacies consists of coralline and algal boundstone that weathers gray, dark gray, and maroon. Beds are lenticular, extend up to 15 m along local strike, and are up to 0.5 m thick. Coralline boundstone consists primarily of *Syringipora* (Figure 4-9), but *Lithostrotionella* is widespread and locally abundant. *Syringipora* corals up to 60 cm in diameter and *Lithostrotionella* up to 30 cm in diameter have been observed in growth position. Corallites in both varieties of are generally partially silicified and dolomitized, and filled with a range of

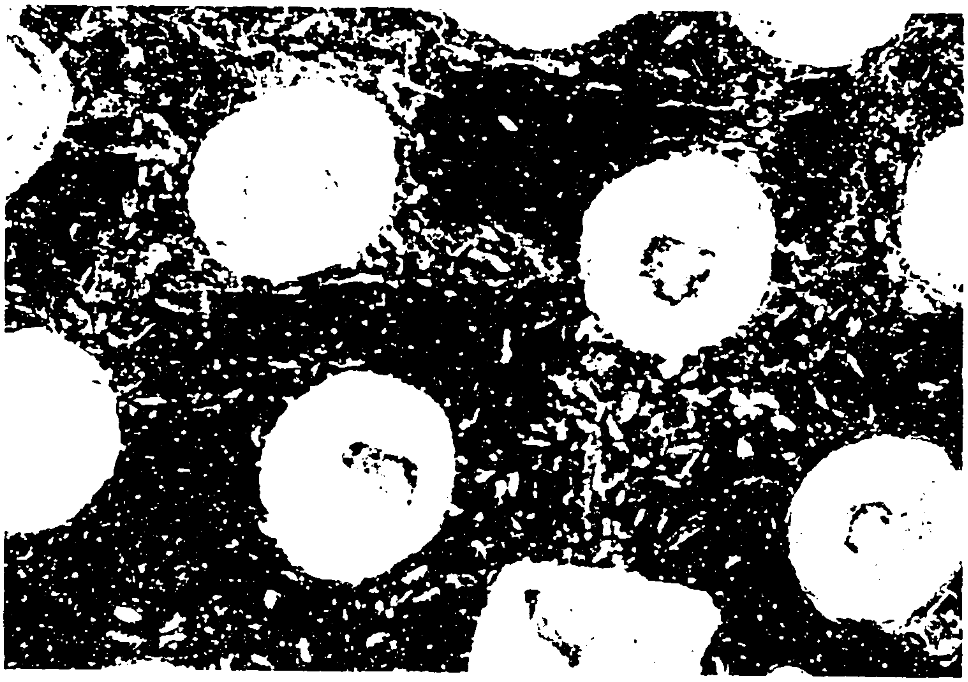


Figure 4-9 - Photomicrograph of coralline/algal boundstone lithofacies. *Syringipora* coral with silicified corallites and argillaceous spiculitic wackestone/packstone between corallites. Scale is 1 cm = 1.48 mm.

argillaceous lithologies including spiculitic and pelmatozoan packstone, wackestone, and lime mudstone. Corallites are locally filled with calcite spar. Original void space between corallites in *Syringiporas* corals are filled with argillaceous spiculitic and less commonly pelmatozoan packstone, wackestone, and lime mudstone. Coralline boundstone is distinctive because of its association with dark-colored, argillaceous carbonate lithologies, both as sediment within and between coral heads and enclosing the boundstone masses. Algal boundstone is much less common than coralline boundstone, but where present consists of *Stacheiinids* (red algae; Wray, 1977) and other varieties of alga of uncertain affinity.

The coralline/algal boundstone iithofacies was deposited in relatively shallow water, marginally restricted- to open-platform settings. Hermatypic corals (all pre-Mesozoic forms) and red algae are most common in shallow water <25 m deep (Flugel, 1982; Heckel, 1972; Wilson, 1975). The common argillaceous, spiculitic carbonate lithologies that fill the void space between septa in coralline boundstone suggest deposition in muddy, marginally restricted environments (e.g. Wilson, 1975). These species of coral are known for their ability to thrive in muddy environments (Wilson and Jordan, 1983).

LITHOLOGIC SUCCESSIONS

The upper Kayak Shale is the depositional record of repeated failures to establish a carbonate platform in the rift-flank region of a passive continental margin. The nature of this terrigenous clastic-to-carbonate transition varies considerably along and across depositional strike - approximately east-west and north-south, respectively. In order to focus on the mechanisms controlling the transition to and establishment of a carbonate platform above the muddy Kayak shelf, we have defined several types of parasequences and acyclic successions based on lithofacies sequences. The parasequences and acyclic successions consist of lithofacies described in the previous section. The term parasequence is used as defined by Van Wagoner et al. (1988). In this section, we describe three types of parasequence and three acyclic successions recognized in the upper Kayak Shale. More detailed sampling (0.5 m interval) may reveal cyclicity in the apparently acyclic successions.

Shale-Dominated Parasequences

Shale-Dolomitic Sandstone

Shale-dolomitic sandstone parasequences form upward-coarsening and -thickening successions 2 to 14 m thick, are dominated by the black shale lithofacies, and are capped by the dolomitic sandstone with local minor interbedded spiculitic lime mudstone/wackestone (Figures 4-10 and 4-11). They begin with black, fissile clay shale in sharp contact above dolomitic sandstone of the underlying parsequence and pass gradually upsection into black shale with lenticular laminae of the dolomitic sandstone. Lenticular laminae lack visible bioturbation. Interlaminated shale and sandstone pass upsection into shale with thinly interbedded, bioturbated, argillaceous dolomitic sandstone and, ultimately, into burrow-mottled dolomitic sandstone caps. An abrupt upward change in lithology from burrow-mottled dolomitic sandstone to black clay shale marks the upper contact of each shale-dolomitic sandstone parasequence.

Shale-dolomitic sandstone parasequences record gradual shoaling above a low-energy, anaerobic bottom layer in restricted-platform settings. The oxygen-depleted bottom layer probably developed due to, and was sustained by, large influxes of land-derived organic material and poor water circulation on the muddy shelf. The change upsection to bioturbated dolomitic sandstone suggests that each parasequence records a gradual increase in the dissolved oxygen content. The degree of bioturbation in dolomitic sandstone near the tops of

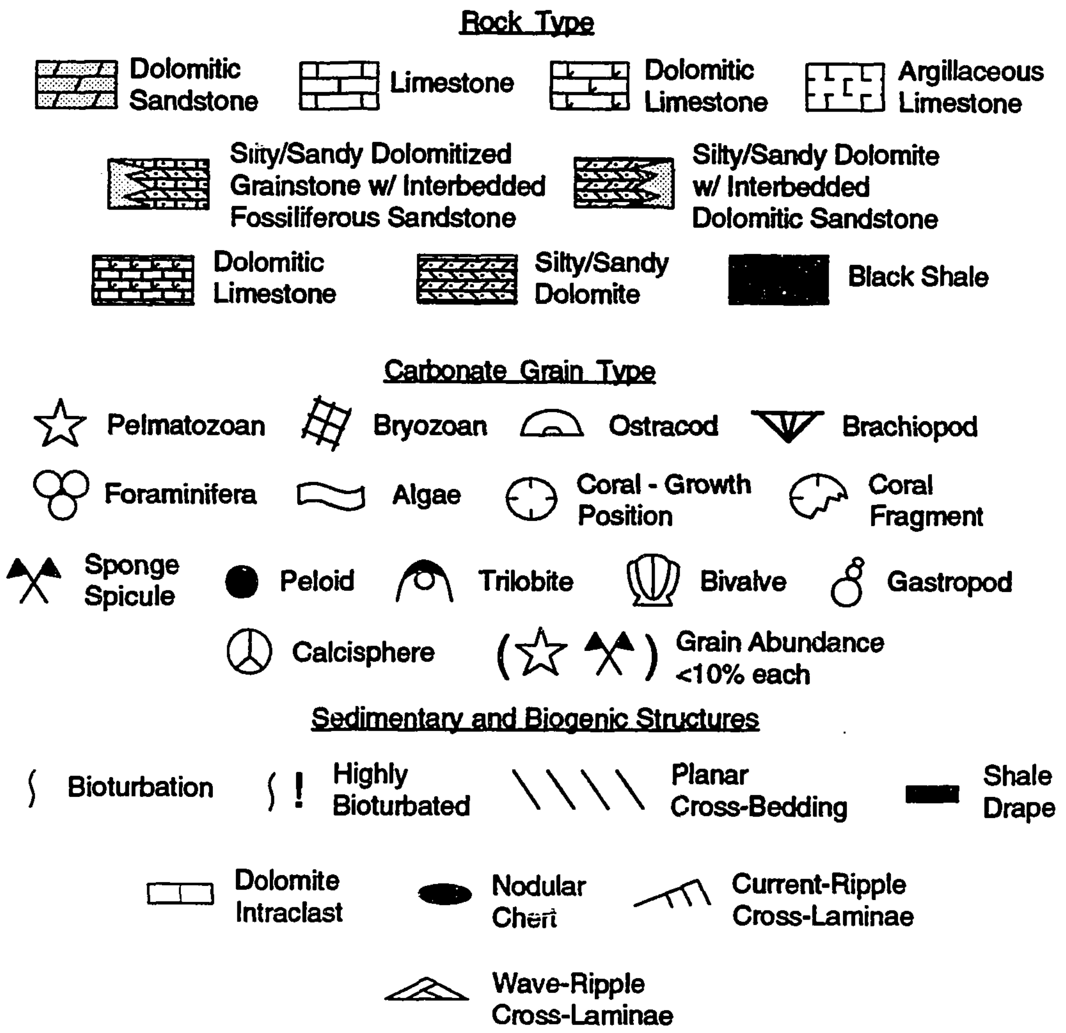


Figure 4-10 - Explanation of symbols used in Figures 4-11 through 4-16.

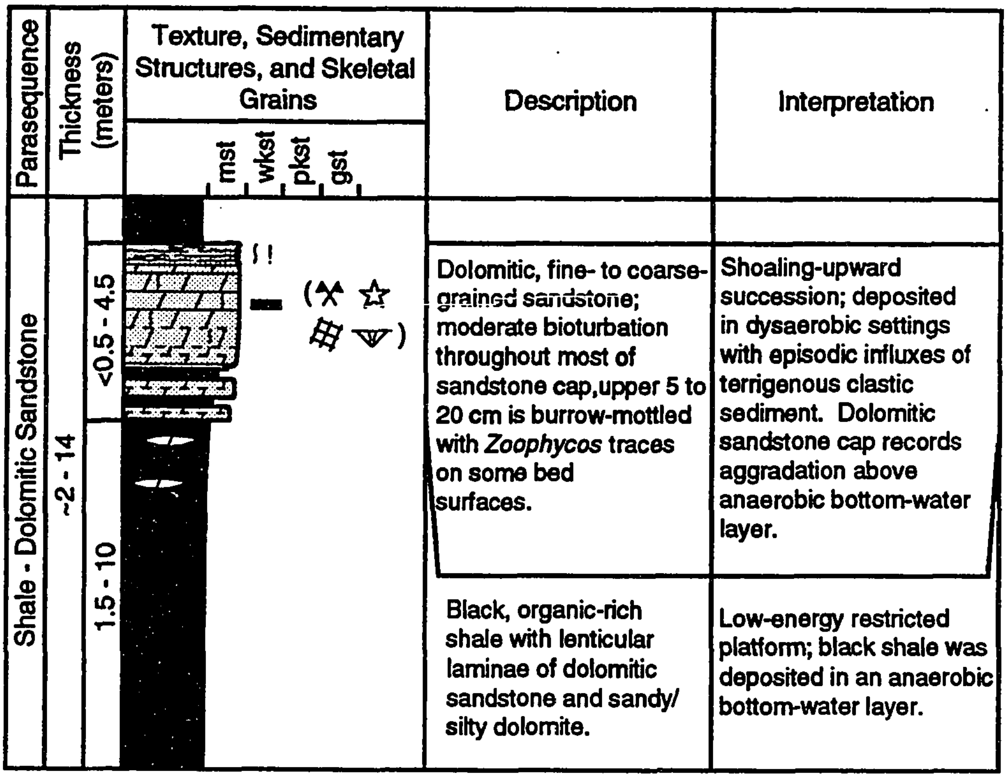


Figure 4-11 - Generalized column of shale-dolomitic sandstone parasequence. See Figure 4-10 for explanation of symbols.

these parasequences, common *Zoophycos* burrows, and sparse shelly fauna indicate deposition in dysaerobic settings where burrowing organisms could thrive, but the environment was too stressful for a diverse, abundant shelly fauna (Ekdale and Mason, 1988). The upward increase in oxygenation was accomplished by progradation, aggradation, and associated shoaling of the depositional surface above an oxygen-depleted bottom-water layer. The sharp contacts between the dolomitic sandstone and overlying black shale lithofacies at the tops of these parasequences record abrupt changes in depositional conditions caused by major influxes of terrigenous clastic mud, or by changes in relative sea-level.

Shale-Limestone

Shale-limestone parasequences form upward-thickening successions 2 to 25 m thick, are dominated by the black shale lithofacies, and consist of a variety of argillaceous carbonate lithologies at the top (Figure 4-12). Because a wide variety of limestones may form the upper part, Figure 4-11 is an idealized representation of a shale-limestone parasequence. Each parasequence begins with black clay shale in sharp contact with skeletal carbonate of the underlying parasequence. Homogeneous black shale passes gradually upsection into black shale with millimeter- and centimeter-scale lenticular laminae of argillaceous spiculitic lime mudstone, wackestone, and packstone. These generally grade upsection into either interbedded black shale and one of the spiculitic lithologies, or directly into thicker beds of skeletal carbonate that cap most shale-limestone parasequences. Skeletal carbonate rocks near the tops of parasequences consist of pelmatozoan lime mudstone, wackestone and packstone (Figure 4-12). Lenses of coralline boundstone are interbedded with the muddy carbonate lithologies locally, and pelmatozoan grainstone caps some shale-limestone

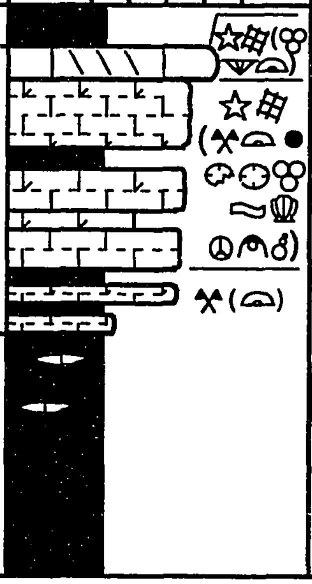
Parasequence	Thickness (meters)	Texture, Sedimentary Structures, and Skeletal Grains (mst, wkst, pkst, gst)	Description	Interpretation
Shale - Limestone	2 - ~25; <0.5 - 7		Skeletal carbonate; local coralline boundstone; +- dispersed clay; dispersed quartz sand/silt, up to 30%; *Syringipora* & *Lithostrotionella* locally in growth position and as reworked fragments; vertical sequence is variable, grainstone caps commonly lacking, general trend is toward grainy lithologies up-section; shale drapes and thin shale breaks common.	Shoaling-upward succession records localized buildups deposited in marginally restricted- to open-platform setting. Limestones record progressive shoaling above anaerobic bottom-water layer, local grainstone caps record shoaling, possibly to intertidal zone.
	1.5 - 23		Black shale.	Restricted-platform setting with anaerobic bottom-water layer.

Figure 4-12 - Generalized column of shale-limestone parasequence. See Figure 4-10 for explanation of symbols.

parasequences. An abrupt upward change in lithology from grainy skeletal limestone to clay shale marks the upper contacts of shale-limestone parasequences.

Shale-limestone parasequences record gradual shoaling above a low-energy, anaerobic bottom layer that developed due to large influxes of land-derived organic material and poor water circulation over a muddy shelf in restricted-platform settings. The change upsection to argillaceous spiculitic carbonate lithologies suggests that conditions gradually became favorable for sponges to colonize the muddy substrate. Conditions were still restricted - dysaerobic to marginally dysaerobic - as indicated by an impoverished fauna of sponge spicules and limited numbers of brachiopods, pelmatozoans, bryozoans, and the enclosing black shale. Locally, these early colonization attempts resulted in the sediment-water interface aggrading above an anaerobic bottom-water layer to shallower depths, where aerobic, open-platform conditions supported a rich fauna dominated by pelmatozoans and bryozoans. Coralline and algal boundstone thrived in these shallow-water conditions. Some shale-limestone parasequences shoaled to shallow subtidal and intertidal depths as indicated by packstone and locally grainstone. The upward change in lithology across the upper contacts of shale-limestone parasequences records an abrupt change in depositional conditions caused by major influxes of terrigenous clastic mud, or changes in relative sea-level.

Carbonate-Dominated Parasequences

Wackestone-Packstone

Wackestone-packstone parasequences form 1 to 12 m thick successions that pass gradually upsection from argillaceous pelmatozoan lime mudstone and/or wackestone to pelmatozoan packstone (Figure 4-13). Coralline boundstone is a common lithology within these parasequences and may be present at any level in the succession. Pelmatozoan

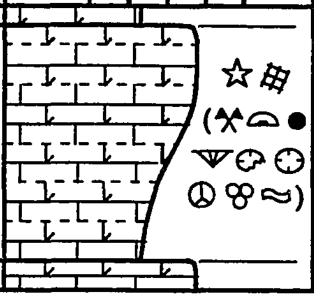
Parasequence	Thickness (meters)	Texture, Sedimentary Structures, and Skeletal Grains mst wkst pkst gst	Description	Interpretation
Wackestone-Packstone	0 - 5		Skeletal carbonate; local coralline boundstone with *Syringipora* at any level in succession and local grainstone caps ; +- dispersed clay; dispersed quartz sand/silt (up to 30%), common nodular chert.	Shoaling-upward succession deposited in open-platform setting. Local grainstone caps record skeletal sand shoals deposited above fairweather wave-base (4-6 m) and in tidal inlets.

Figure 4-13 - Generalized column of wackestone-packstone parasequence. See Figure 4-10 for explanation of symbols.

grainstone may cap wackestone-packstone parasequences locally and commonly thickens along local strike. Contacts between grainstone and other lithologies are sharp and locally erosional. An abrupt upward change in lithology from grainy skeletal limestone to muddy skeletal limestone marks the upper contacts of wackestone-packstone parasequences.

The gradual transition upsection from argillaceous skeletal carbonate lithologies to grainy lithologies indicates progressive shoaling to depths near fairweather wave-base and increased winnowing of lime mud in open-platform settings. Pelmatozoan lime mudstone and wackestone at the base of each parasequence indicate deposition in open-platform settings, below fairweather wave-base. The gradual transition upsection to packstone indicates progressive shoaling to shallow subtidal depths, near or just above fairweather wave-base, and locally developed grainstone that caps some parasequences indicates deposition at intertidal depths associated with skeletal sand shoals. The upward change in lithology across the upper contacts of wackestone-packstone parasequences records abrupt changes in depositional conditions due to large influxes of terrigenous clastic mud. These incursions of mud resulted in turbid water conditions, which were lethal to open-marine filter-feeding organisms - i.e. pelmatozoans and bryozoans.

Acyclic Successions

Packstone

Acyclic packstone successions up to 16 m thick consist primarily of dark gray to dark brown argillaceous, spiculitic packstone (Figure 4-14). Spiculitic packstone successions are thinly bedded and include local discontinuous shale drapes up to 0.5 cm thick between beds. In addition to sponge spicules, peloids are widespread and locally approach spicules in abundance. Pelmatozoan packstone/grainstone and coralline boundstone are interbedded

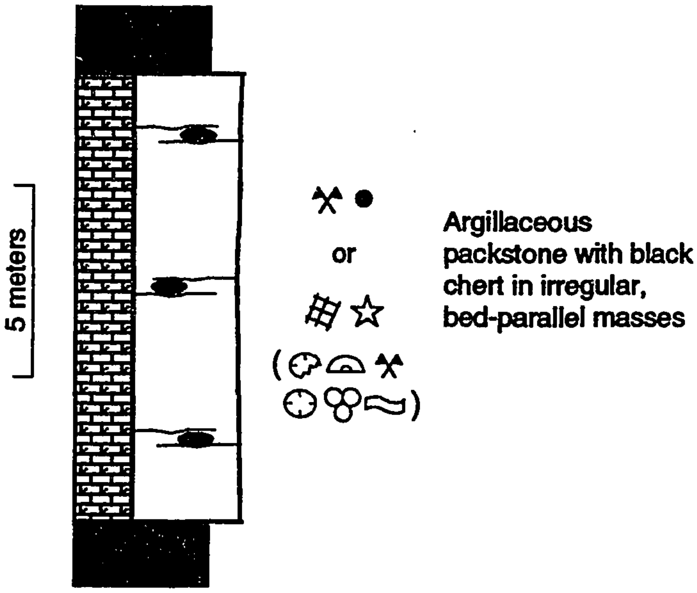


Figure 4-14 - Generalized column of acyclic packstone succession. Acyclic pelmatozoan packstone successions have been observed, but are less common. See Figure 4-10 for explanation of symbols.

locally, but each forms a minor component of these successions. Dark gray and black nodular chert is common. Packstone successions are enclosed within black shale and succession-bounding contacts are sharp (Figure 4-14).

Acyclic packstone successions record deposition in low-energy marginally restricted platform settings, below fairweather wave-base. Abundant spicules, peloids, and argillaceous material suggest restricted conditions (Flugel, 1982; Wilson, 1975). The stratigraphic position of packstone successions within black shale sequences and common black shale drapes between packstone beds suggest dysaerobic to marginally dysaerobic conditions. Minor interbedded pelmatozoan packstone/grainstone indicates either abrupt fluctuations in environmental conditions - i.e. temporary improvement in water circulation leading to aerobic conditions - or transport from distant open-platform settings by storm-generated flows. Minor coralline boundstone support the former alternative. The sharp contact with overlying black shale records an abrupt change in depositional conditions caused by a major influx of terrigenous clastic mud.

Grainstone-Fossiliferous Sandstone

Acyclic grainstone-fossiliferous sandstone successions are up to 76 m thick and consist of interlaminated pelmatozoan grainstone, sandy grainstone, and interbedded fossiliferous sandstone (Figure 4-15). Skeletal grains are characterized by low to moderate abrasion. Sets of wave-ripple cross-laminae are abundant. These successions are periodically interrupted by fossiliferous sandstone sequences up to 2 m thick. Wave-ripple cross-laminae are common in sandstone sequences.

Grainstone-sandstone successions were deposited in open-platform settings above fairweather wave-base, probably as mixed skeletal/quartz sand shoals. The supply of sand-

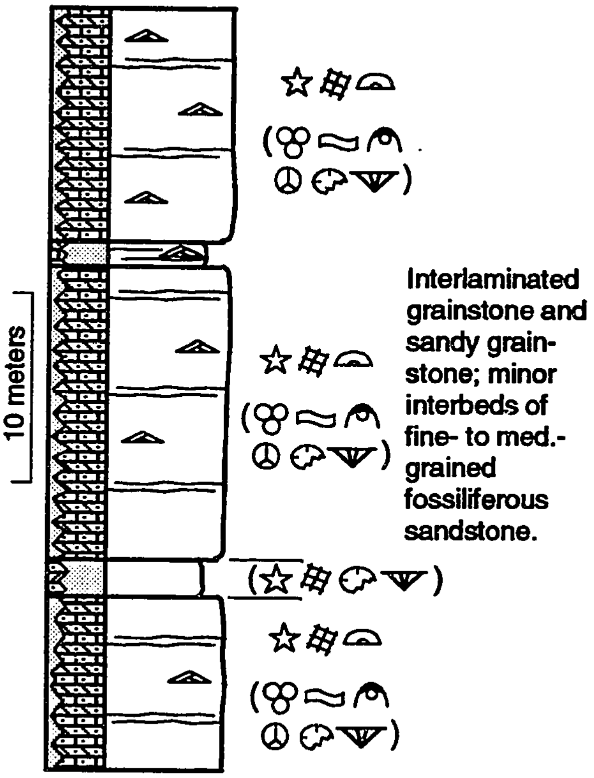


Figure 4-15 - Generalized column of acyclic grainstone-fossiliferous sandstone succession. See Figure 4-10 for explanation of symbols.

sized terrigenous clastic sediment to this setting was relatively high and constant. Abundant wave-ripple cross-laminae and low to moderate grain abrasion suggest that the environment was constantly agitated, but was not characterized by high energy. The origin of sandstone sequences is uncertain because their geometry is poorly known. Sandstone sequences either record deposition in tidal inlets that cut across shoals, or deposition on shoals as storm-generated sand sheets. The sharp contact with overlying black shale records an abrupt change in depositional conditions caused by a major influx of terrigenous clastic mud, or changes in relative sea-level.

Dolomudstone

Acyclic dolomudstone successions up to 100 m thick consist primarily of fine-grained dolomite and minor amounts of interbedded dolomitic sandstone and spiculitic packstone (Figure 4-16). Shale drapes are present throughout, but are most abundant and thickest (0.5 to 1.0 cm) in the lower 15 to 25 m. In general, dolomudstone successions are characterized by a gradual increase upsection in the frequency of laterally continuous dolomitic sandstone, spiculitic dolomudstone, and wackestone interbeds and in the degree of bioturbation. Different lithologies are confined to well-segregated beds. Bioturbate structures consist of horizontal traces that resemble *Planolites* (e.g. Benyon and Pemberton, 1992; Hantzschel, 1975; Pemberton et al., 1992). Dolomitic sandstone interbeds contain current-ripple cross-laminae locally. Dolomudstone successions are abruptly overlain by black shale.

Dolomudstone successions record deposition in restricted-platform settings as carbonate tidal flats. The upward increase in dolomitic sandstone, spiculitic packstone, and degree of bioturbation suggests progressive flooding and eventual inundation of the carbonate tidal flat by marine waters. Different lithologies are confined to well-segregated

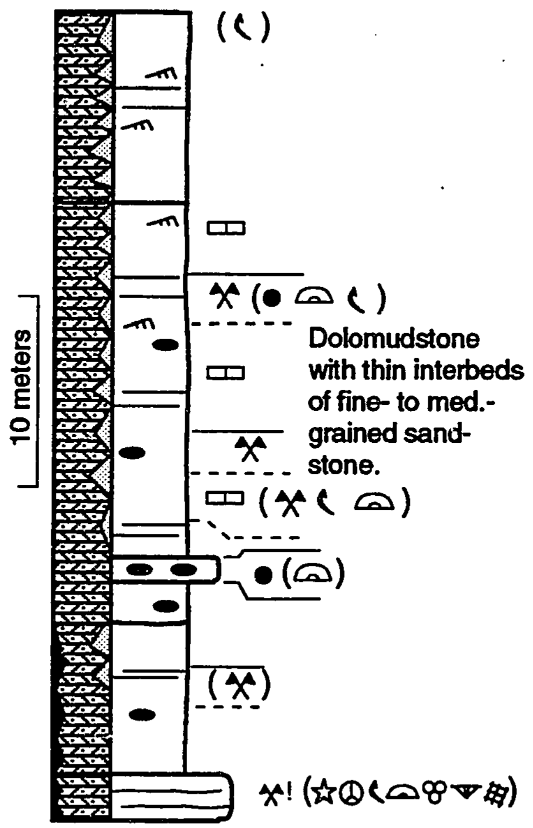


Figure 4-16 - Generalized column of acyclic dolomudstone succession. See Figure 4-10 for explanation of symbols.

beds, which suggests their deposition by different mechanisms. Sandstone beds lack body fossils and are laterally continuous, which suggests deposition from land-derived sheet floods (e.g. Schreiber, 1986). In contrast, packstone beds contain a low-diversity fauna dominated by sponge spicules, which suggests derivation from a restricted-platform, subtidal setting and subsequent transportation on to the carbonate tidal-flat by storm-generated flows (e.g. Shinn, 1983). This succession closely resembles tidal-flat successions in Cambro-Ordovician strata from the Mohawk Valley-Saratoga Springs region in New York (U.S.A.), which consist of laminated crystalline dolomite (laminae of clean dolomite, argillaceous organic-rich dolomite, and silty/sandy dolomite) and interbedded dolomitic sandstone (Mazzullo et al., 1978). The sharp contact with overlying black shale records an abrupt change in depositional conditions caused by a major influx of terrigenous clastic mud.

STRATIGRAPHIC RELATIONS AND PALEOGEOGRAPHY

The paleogeographic distribution of parasequences and acyclic successions defines two depositional sub-basins separated by the Devonian Okpilak Batholith, that are referred to herein as the eastern and western sub-basins (Figure 4-17). In this section we discuss stratigraphic relations between parasequences and acyclic successions and their implications for Carboniferous paleogeography.

Western Sub-Basin

Shale-dominated successions consisting of the shale-dolomitic sandstone and shale-limestone parasequences form the upper Kayak Shale at most locations in the western sub-basin, although acyclic packstone successions occur at the Kayak-Lisburne transition at two locations (Locations 15 and 16 on Figure 4-3). In the western Shublik Mountains (Location 1

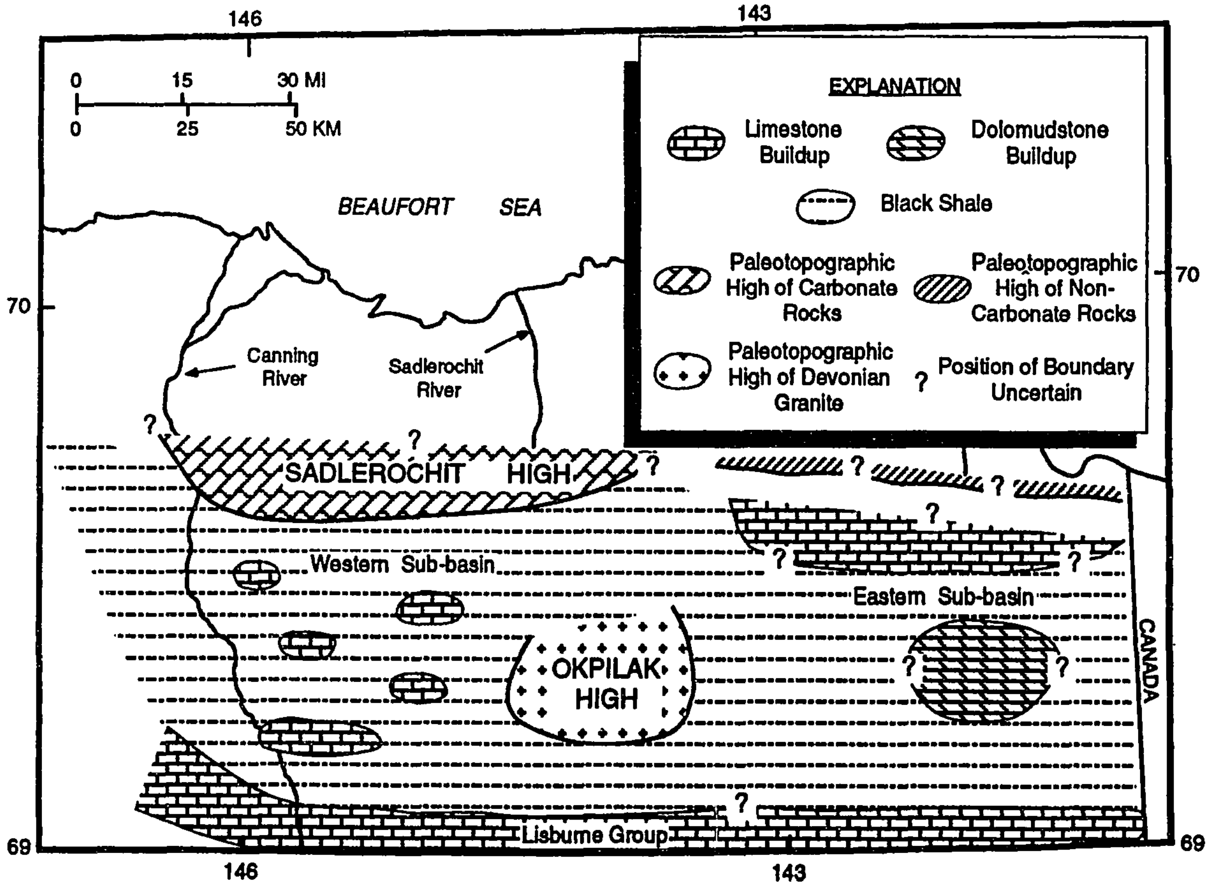
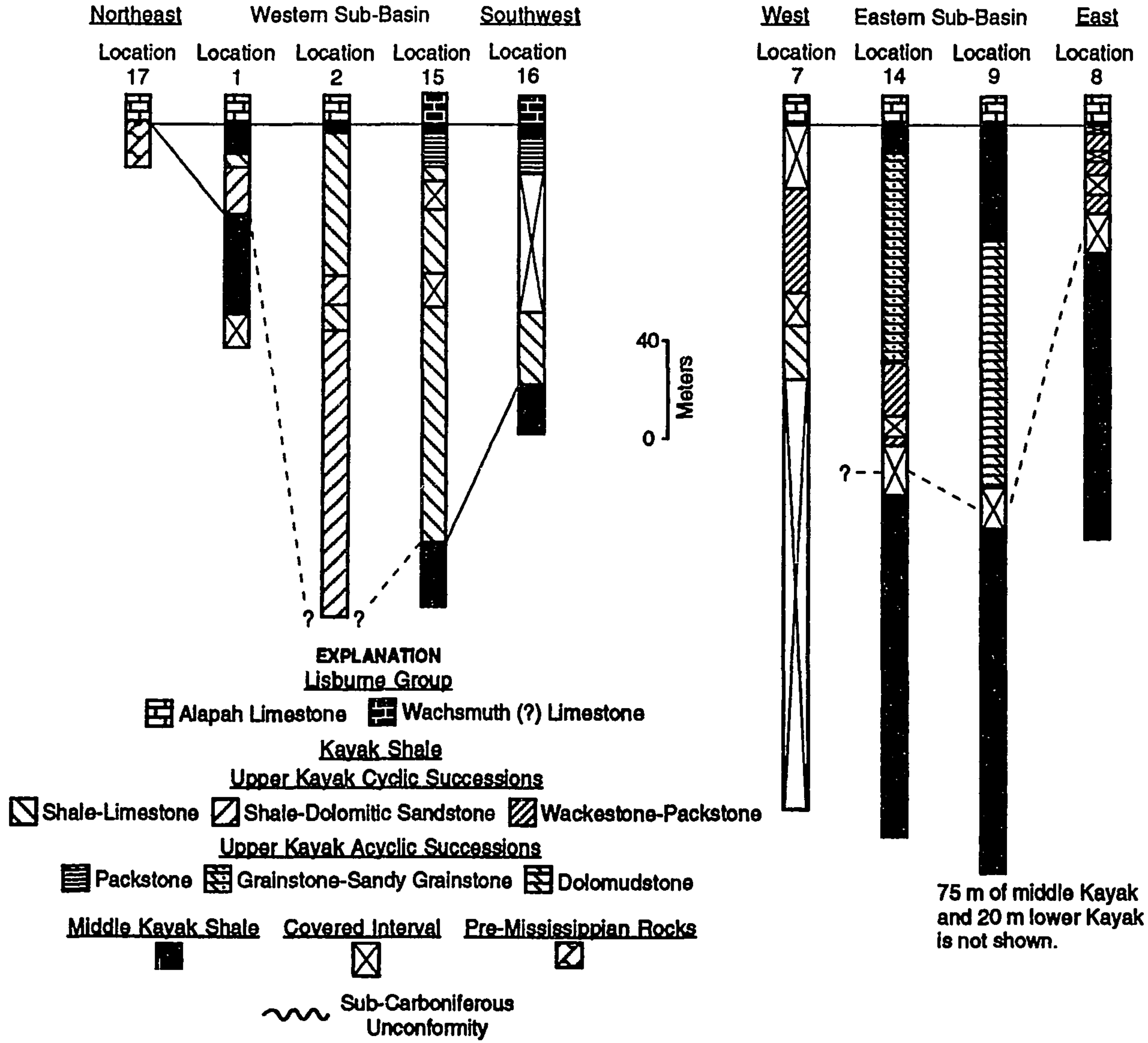


Figure 4-17 - Generalized paleogeographic reconstruction for late Visean. Distribution of parasequences and acyclic successions defines two sub-basins. Western sub-basin is shale-dominated and filled with shale-dolomitic sandstone parasequences, shale-limestone parasequences, and minor acyclic packstone successions. The eastern sub-basin is carbonate-dominated and filled with minor shale-limestone and wackestone-packstone parasequences, and thick acyclic successions of grainstone-fossiliferous sandstone and dolomudstone.

on Figure 4-3), the upper Kayak Shale consists of three shale-dolomitic sandstone parasequences and one shale-limestone parasequence situated below a 15 to 20 m thick shale break below the Alapah Limestone (Figure 4-18). Abundant shale-dolomitic sandstone parasequences near the base of the upper Kayak Shale suggest a paleogeographic position relatively close to the strand line and terrigenous clastic source areas at the onset of upper Kayak deposition (Flugel, 1982; Wilson, 1975). Shale-dolomitic sandstone parasequences grade up section to shale-limestone parasequences and reflect gradual northward migration of the strand line and terrigenous clastic source areas. The basal Alapah Limestone here consists of interbedded peloidal packstone and dolomudstone with common calcite spar-filled fenestrae, and records deposition in a restricted-platform setting (LePain, unpublished data). The lack of abundant terrigenous clastic sediment in the basal Alapah indicates additional northward migration of the strand line due to transgression.

Farther south, in the central Fourth Range (Location 2 on Figure 4-3), the lower 90+ m of the upper Kayak Shale consists of shale-dolomitic sandstone parasequences (Figure 4-18). These are gradationally overlain by shale-limestone parasequences. Pelmatozoans and bryozoans dominate the carbonate grain population in all shale-limestone parasequences except the stratigraphically highest one, in which siliceous sponge spicules dominate the grain population. The gradual transition upsection from shale-dolomitic sandstone to shale-limestone parasequences indicates a paleogeographic position that was initially close to the strand line and terrigenous clastic source areas. With continued transgression, the strand line migrated northward and shale-dolomitic sandstone parasequences were gradually replaced by the shale-limestone parasequences. The contact with the Alapah Limestone is placed at the top of a 3 m shale break. The basal beds of the Alapah Limestone consist of interbedded algal

Figure 4-18 - Cross-sections through the western and eastern sub-basins. Cross-sections illustrate the geographic and stratigraphic distribution of parasequences and acyclic successions.


Northeast
Western Sub-Basin
Southwest
Location 17
Location 1
Location 2
Location 15
Location 16
West
Eastern Sub-Basin
East
Location 7
Location 14
Location 9
Location 8
40
0
Meters
?
?
?
EXPLANATION
Lisburne Group
Alapah Limestone
Wachsmuth (?) Limestone
Kayak Shale
Upper Kayak Cyclic Successions
Shale-Limestone
Shale-Dolomitic Sandstone
Wackestone-Packstone
Upper Kayak Acyclic Successions
Packstone
Grainstone-Sandy Grainstone
Dolomudstone
Middle Kayak Shale
Covered Interval
Pre-Mississippian Rocks
Sub-Carboniferous Unconformity
75 m of middle Kayak and 20 m lower Kayak is not shown.

boundstone, cryptalgal dolomite, spiculitic lime mudstone, and spiculitic dolomudstone, and record deposition in low-energy restricted- and open-platform settings (Gruzlovic, 1991).

Farther south, in the central Franklin Mountains (Location 15 on Figure 4-3), shale-limestone parasequences form the upper Kayak Shale (Figure 4-18). Parasequences are generally thicker here than at locations to the north (Locations 1 and 2 on Figure 4-18). Pelmatozoans and bryozoans dominate the carbonate grain population in the shale-limestone parasequences, however, siliceous sponge spicules and peloids are locally abundant. The contact with the Wachsmuth (?) Limestone (or the Alapah Limestone) is placed at the top of a 3.5 m thick shale break. The basal beds of the Wachsmuth (?) consist of argillaceous peloidal, spiculitic packstone with abundant black shale drapes and are similar to the spiculitic wackestone/packstone lithofacies recognized elsewhere in the upper Kayak Shale (e.g. LePain and Crowder, 1991). The basal Wachsmuth (?) Limestone was deposited in an open to slightly restricted (marginally dysaerobic?) platform setting below fairweather wave-base. Common argillaceous material and minor silt- and sand-sized detrital quartz in the upper Kayak Shale and the character of the basal Wachsmuth suggest a paleogeographic position offshore and more distant from terrigenous clastic source areas than Locations 1 and 2 (Figures 4-3 and 4-18).

At Location 16, shale-limestone parasequences form the base of the upper Kayak Shale and a single acyclic spiculitic packstone succession 12 m thick is situated near the top. Parasequences are poorly defined because they are capped only by thin successions of spiculitic or pelmatozoan packstone and are poorly exposed. The contact with the Wachsmuth (?) Limestone is placed at the top of a 8.5 m shale break (Figure 4-18). The basal beds of the Wachsmuth (?) consist of abundant spiculitic packstone and minor siliceous, dolomitic, pelmatozoan wackestone and packstone (LePain and Crowder, 1990). The basal Wachsmuth

(?) Limestone was deposited in an open to restricted (marginally dysaerobic?) platform setting below fairweather wave-base. Common argillaceous material and the lack of silt- and sand-sized terrigenous clastic grains in the upper Kayak Shale and the character of the basal Wachsmuth suggest a paleogeographic position relatively far from the strand line and terrigenous clastic source areas.

At Location 6 (Figure 4-3), the organization of the Kayak Shale is difficult to determine due to extensive talus cover and structural disruption. Mamet and Armstrong (1972) show ~277 m of shale with minor interbeds of siliceous limestone and dolomite below the Alapah Limestone near this location. Small isoclinal folds are common throughout the exposed Kayak Shale at this location, which suggests that the thickness reported by Mamet and Armstrong (1972) reflects structural thickening. However, columnar sections from this location suggest that the upper Kayak Shale is made up of a few relatively thick shale-limestone (and dolomitized limestone) parasequences (LePain and Crowder, 1990; Mamet and Armstrong, 1972). The basal beds of the Alapah Limestone consist of argillaceous, spiculitic-foraminiferal-calcispheric-pelmatozoan-bryozoan packstone and wackestone that record deposition in an open to marginally restricted platform setting (Wood and Armstrong, 1975) below fairweather wave-base. The character of the basal Alapah Limestone suggests a paleogeographic position relatively far from the strand line and terrigenous clastic source areas.

Eastern Sub-Basin

In the eastern sub-basin, shale-limestone and wackestone-packstone parasequences, and grainstone-dolomitic sandstone and dolomudstone acyclic successions form the upper Kayak Shale (Figure 4-18). At the western end of Leffingwell Ridge (Location 7 on Figure 4-3), much of the upper Kayak Shale is concealed by talus, however, dark gray- and maroon-colored shale-limestone parasequences are exposed near the base and dark gray and maroon colored argillaceous wackestone-packstone parasequences near the top (Figure 4-18). Common silt- and sand-sized detrital quartz suggest a paleogeographic position relatively close to the strand line. Black shale approximately five meters thick rests above the stratigraphically highest exposed parasequence in the upper Kayak Shale. The contact with the Alapah Limestone is arbitrarily placed in the middle of a section 40 to 45 m thick that is covered by talus. Talus cover consists of light- to medium-gray weathering lime mudstone, wackestone, and packstone and the next exposures upsection are of light- to medium-gray weathering peloidal packstone and pelmatozoan-peloidal grainstone of the Alapah Limestone (LePain and Crowder, 1991). Skeletal grains are highly micritized. The basal, exposed Alapah Limestone records deposition in shallow-water restricted- and open-platform settings.

Farther east along Leffingwell Ridge (Location 14 on Figure 4-3), the lower beds of the upper Kayak Shale consist of approximately 30 to 35 m of wackestone-packstone parasequences (Figure 4-18). These parasequences are abruptly overlain by an acyclic succession of grainstone-fossiliferous sandstone 75 to 80 m thick. Abundant silt- and sand-sized detrital quartz suggests a paleogeographic position very close to the strand line and terrigenous clastic sources (possibly the Barrow arch). The grainstone-fossiliferous sandstone succession is abruptly overlain by ~15 m of black clay shale. The contact with the overlying Alapah Limestone is placed at the top of this shale break, and the basal beds of the Alapah consist of ostracod, peloidal lime mudstone and wackestone (LePain and Crowder, 1991) that record deposition in low-energy, restricted-platform settings.

Near Clarence River (Location 8 on Figure 4-3), a poorly exposed succession of lime mudstone, packstone, and grainstone forms the upper Kayak Shale (Figure 4-18). Common silt- and sand-sized detrital quartz in limestones and interbedded fossiliferous sandstone suggest a paleogeographic position relatively close to the strand line and terrigenous clastic source areas to the north and east (possibly the Barrow arch). The contact with the Alapah Limestone is arbitrarily placed in the middle of a section 10 m thick that is covered by talus, above which light gray-weathering ostracod, peloidal wackestone and packstone and cryptalgal (?) lime mudstone are exposed. The basal beds of the Alapah Limestone record deposition in a low-energy restricted-platform setting.

In the next outcrop belt south of Leffingwell Ridge (Location 9 on Figure 4-3), an acyclic succession of dolomudstone 90 to 100 m thick forms the upper Kayak Shale (Figure 4-18). Abundant silt- and sand-sized detrital quartz and common interbedded dolomitic sandstone in this succession, and its distance south from possible terrigenous clastic sources areas north of Leffingwell Ridge, suggest that a paleotopographic high was present during Kayak deposition and located farther east (possibly the Barrow arch in the northern Yukon Territory). The dolomudstone succession is abruptly overlain by a poorly exposed succession of black shale 50+ m thick . The contact with the Alapah Limestone is not exposed, but shale in the tundra cover immediately below suggests that it is sharp. The basal beds of the Alapah Limestone consist of light-gray weathering interbedded foraminifera, calcispheric packstone and pelmatozoan wackestone and packstone (LePain and Crowder, 1991). The basal Alapah Limestone records deposition in an open-platform setting.

DEPOSITIONAL RECONSTRUCTION

In the northeastern Brooks Range, terrigenous clastic rocks of the Endicott Group onlap an irregular, low-relief unconformity surface toward the north and northeast. In this region, the Endicott Group records deposition in a rift-flank region landward of the tectonic hinge zone in a passive continental margin setting (LePain et al., in review). Initially, fluvial and marginal-marine sediments of the Kekiktuk Conglomerate and lower Kayak Shale, respectively, were deposited in incised paleovalleys with local relief up to ~128 m (LePain and Crowder, 1992b). As transgression proceeded, local paleotopographic highs were gradually onlapped and buried beneath fine-grained marginal- and shallow-marine terrigenous clastic sediment of the middle Kayak Shale. Positive areas, such as the well-known Sadlerochit and Okpilak highs remained emergent throughout Kayak deposition and were major sources for terrigenous clastic sediment (Figure 4-18). The Barrow arch may also have been a significant source of terrigenous clastic sediment in the upper Kayak Shale.

Throughout Kayak deposition (Visean), the northeastern Brooks Range was situated in a low-latitude humid climatic zone (Ravn, 1991, 1992; Utting, 1990, 1991a, 1991b; Witzke and Heckel, 1988) and abundant fine-grained terrigenous clastic sediment and terrestrial plant fragments were transported into low-energy marginal- and shallow-marine environments in both sub-basins. The steady supply of argillaceous sediment and plant fragments contributed to widespread oxygen depletion and anaerobic to dysaerobic bottom-water conditions. Black shale deposition dominated both sub-basins throughout much of Kayak time, as recorded in the lower and middle Kayak Shale.

Black shales are extensive in the Devonian and Lower Carboniferous record of Euramerica and suggest widespread density stratification and anoxia in epicontinental seas (Witzke and Heckel, 1988). They are also common at the bases of transgressive successions (Savoy, 1992). Black shale deposition may result on a low-latitude continental shelf that has been flooded with oxygen-depleted water from an oceanic oxygen-minimum zone (Savoy, 1992; Witzke and Heckel, 1988) presumably due to upwelling. Alternatively, they may result in a marine setting where water circulation is restricted by a physical barrier (Byers, 1977; Savoy, 1992; Witzke and Heckel, 1988) - such as a carbonate buildup forming a barrier to circulation on the seaward side of a shelf, or a wide, low-gradient shallow shelf that has an energy-dissipating effect (Enos, 1983).

Regional stratigraphic relations suggest that anaerobic conditions developed due to a steady supply of terrestrial plant material and restricted circulation. Coeval carbonate rocks of the Lisburne Group were being deposited to the south (Armstrong, 1974; Armstrong and Bird, 1974) and probably formed an effective barrier to marine circulation during Kayak deposition to the north. Although the timing of continental breakup (Late Devonian or Early Carboniferous?) and the spreading rate are only speculative, the oceanic basin south of this shallow shelf probably had existed for no more than 20 to 30 ma and may have been narrow enough (< a few hundred kilometers?) to contribute to restricted conditions on the shelf. Conditions of restricted circulation leading to deposition of black shales are characterize some young, narrow ocean basins (e.g. Jenkyns, 1986).

During upper Kayak deposition, the western sub-basin continued to be shale-dominated with only localized sandstone and skeletal limestone buildups (Figures 4-17 and 4-19), whereas, thick and laterally extensive carbonate buildups developed in the eastern sub-basin (Figures 4-17 and 4-20). The upper Kayak Shale records a transition zone between terrigenous clastic-dominated environments to the north and carbonate-dominated environments to the south. In this sense, it is similar to the transition zone that separates coastal terrigenous clastic environments from offshore shallow-water carbonate environments along the modern east coast of Nicaragua (Roberts, 1987).

Western Sub-Basin

In the western sub-basin, shale-dolomitic sandstone and shale-limestone parasequences indicate a close temporal and spatial relation between black shale and

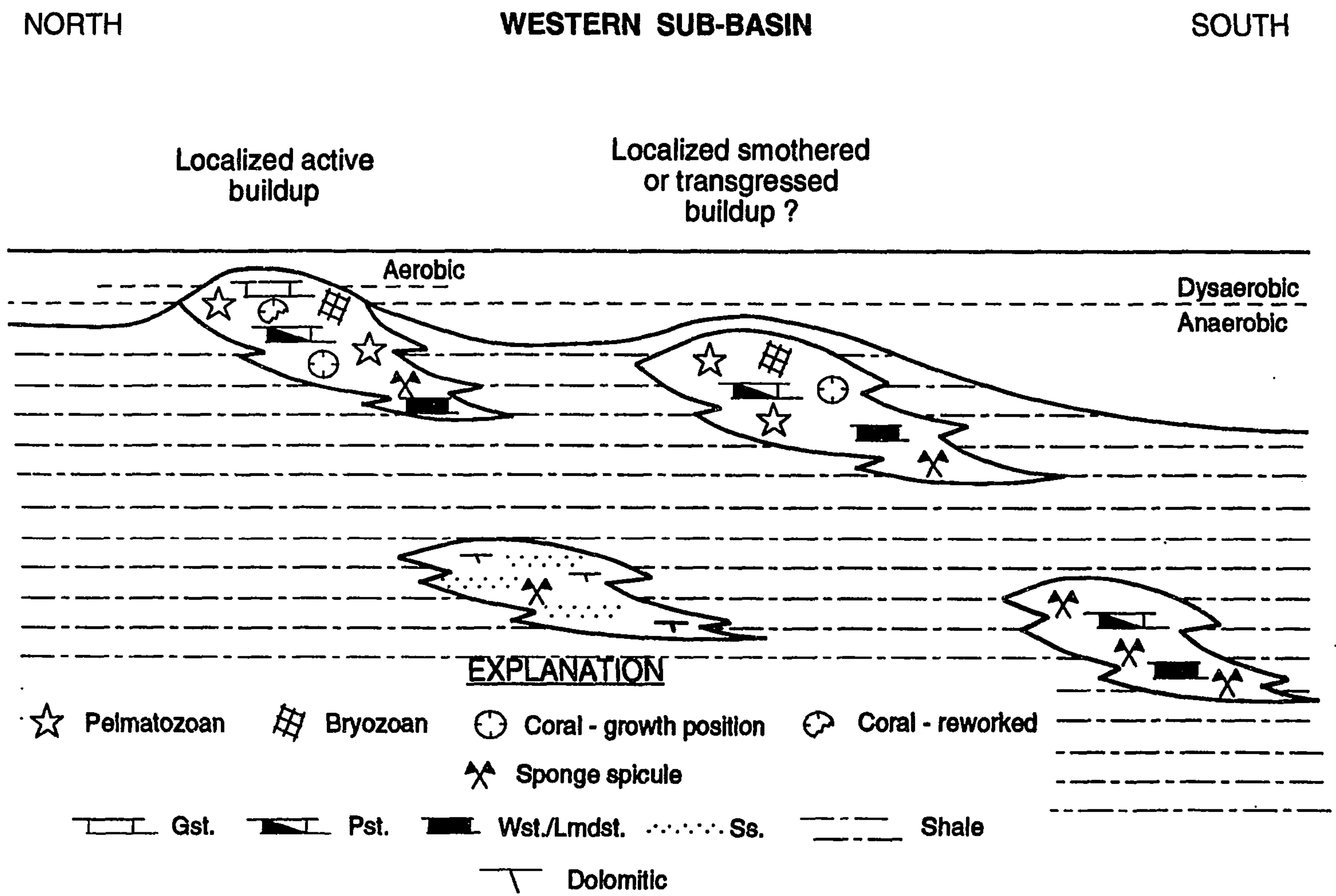


Figure 4-19 - Depositional reconstruction of the western sub-basin. Gst. = grainstone, Pst. = packstone, Wst./Lmdst. = wackestone/lime mudstone, Ss. = sandstone.

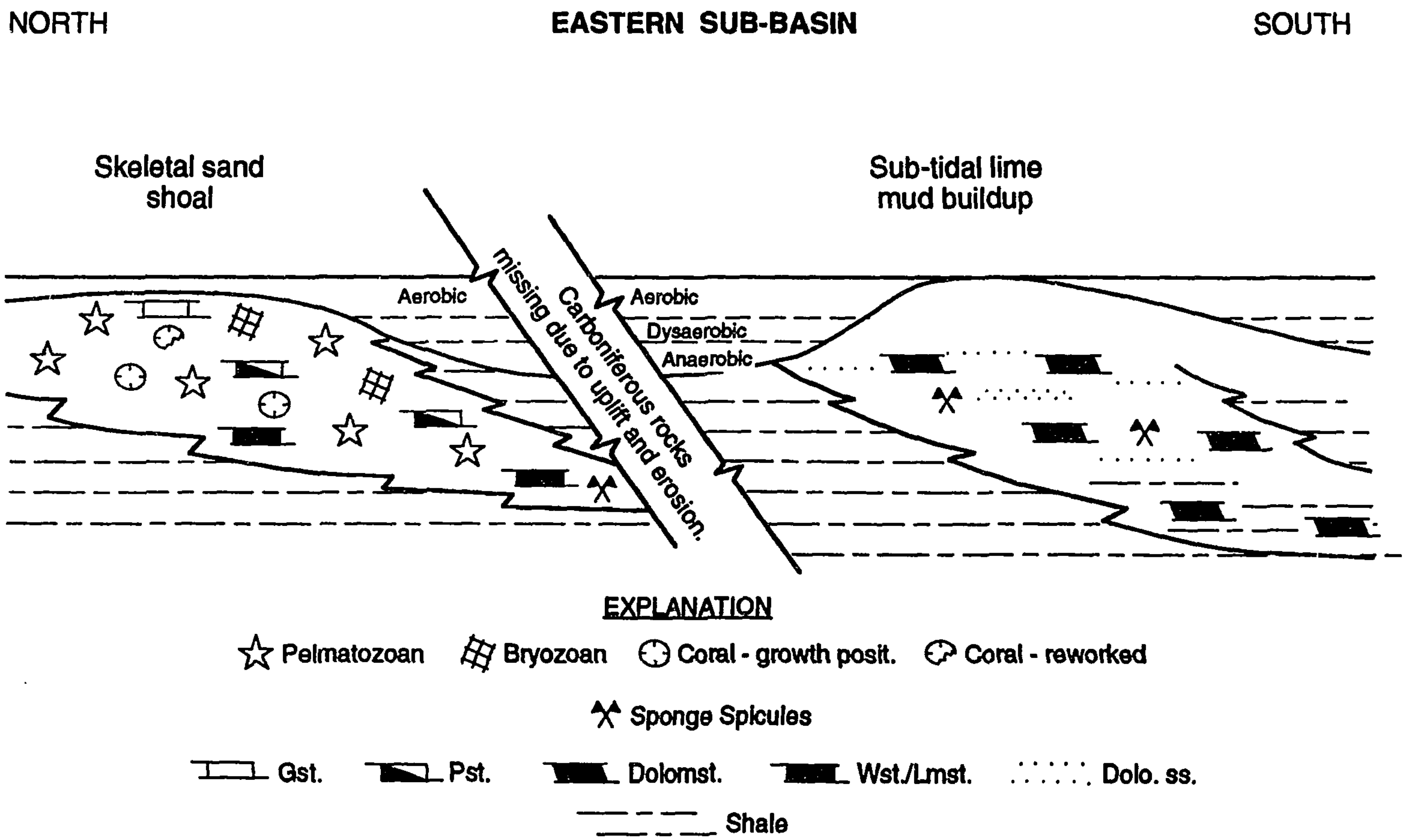


Figure 4-20 - Depositional reconstruction of the eastern sub-basin. Dolomudstone buildup on south side of sub-basin is portrayed as mixed carbonate/terrigenous clastic tidal-flat deposit. Alternatively, dolomudstone succession may record deposition as lime mud buildup below fairweather wave-base and subsequent dolomitization during burial diagenesis.

sandstone deposition first, followed by black shale and skeletal limestone deposition (Figures 4-18 and 4-19). The shale-dominated nature of parasequences and their limited thickness (2 to 25 m) suggest that individual parasequences record small buildups of local extent (Figures 4-17 and 4-19). Locally, black shale deposition was replaced gradually upsection by prograding or aggrading sandy and skeletal carbonate sediments, respectively. It follows from Walther's law that the dysaerobic to aerobic environments recorded in the non-shale lithofacies forming the tops of these parasequences were in close proximity to stagnant, anaerobic environments in which black, terrigenous clastic mud was accumulating (Figures 4-17 and 4-19). The depositional setting of localized carbonate buildups in the shale-dominated western sub-basin is similar to the modern Sunda shelf (Indonesia), where localized carbonate buildups rise above a terrigenous mud-dominated shallow-water shelf in a humid, topical setting that receives an enormous amount of terrigenous clastic mud (Roberts, 1987).

The dolomitic sandstone lithofacies records progradation over an oxygen-depleted bottom layer and the establishment of dysaerobic conditions in which burrowing organisms could thrive along with a sparse, low-diversity shelly fauna. In parasequences at higher stratigraphic levels, black shale gradually passes upsection into sponge buildups (Figure 4-19), which record a fundamental change from anaerobic to marginally dysaerobic and aerobic conditions. This change reflects aggradation above an anaerobic bottom-water layer and records the early colonization attempts of sponges and associated benthic metazoans within a shale-dominated setting. Sponge buildups gradually aggraded into shallow, well-oxygenated waters so that an open-marine fauna dominated by pelmatozoans and bryozoans could thrive (Figure 4-19).

Silt- to coarse-grained quartzose sand that forms the tops of shale-dolomitic sandstone parasequences and common coarse-grained quartzose sediment near the tops of shale-limestone parasequences indicate deposition in environments situated relatively close to the strand line. The transition upsection from shale-dolomitic sandstone to shale-limestone parasequences records gradual northward migration of the strand line and increasing distance from terrigenous clastic sources. Deposition of each shale-dolomitic sandstone and shale-limestone parasequence was abruptly terminated by a large influx of terrigenous mud, probably related to major terrestrial flood events or oceanic storms.

Relatively thin (up to 12 m) acyclic packstone successions have only been recognized in the western sub-basin immediately below the Wachsmuth (?) and Alapah Limestones (Locations 6 and 16 on Figure 4-3). These record sponge buildups of local extent that aggraded above a anaerobic bottom layer into shallower dysaerobic and marginally aerobic waters. Deposition of acyclic packstone successions was abruptly terminated by a major influx of terrigenous clastic mud, after which spiculitic packstone deposition resumed in the overlying Wachsmuth and Alapah Limestones. Spiculitic packstone successions record deposition in the distal areas of the platform where water depths remained below fairweather wave-base throughout upper Kayak and basal Lisburne deposition.

Eastern Sub-Basin

In contrast with the western sub-basin, thick acyclic successions define the upper Kayak Shale in the eastern sub-basin, where deposition of black shale gradually gave way to carbonate sedimentation over a relatively large area (Figures 4-17, 4-18, and 4-20). Although the organization of the upper Kayak Shale varies throughout the eastern sub-basin, the widespread distribution of thick carbonate successions (up to 100 m) suggests that large carbonate buildups developed during upper Kayak deposition (Figure 4-20). Shoaling-upward parasequences of shale-limestone and wackestone-packstone that form the base of the upper Kayak Shale represent early colonization attempts by sponges, pelmatozoans, bryozoans, and *Syringiporid* corals.

The grainstone-fossiliferous sandstone succession was deposited in a shoal environment or as a complex of shoals that developed above fairweather wave-base in the northern part of the eastern sub-basin (Figure 4-20). Interlaminated grainstone and sandy grainstone and fossiliferous and common sandstone interbeds suggests frequent input of fine- to coarse-grained quartzose sand to the shoal environment. This suggests that the shoal/shoal complex occupied a paleogeographic position very close to the strand line and terrigenous clastic source areas (Figures 4-17 and 4-20; e.g. Flugel, 1982; Wilson, 1975).

The dolomudstone succession was deposited in a low-energy carbonate tidal-flat environment (Figure 4-20) that was probably situated in the southeastern part of the eastern sub-basin (Location 9 on Figures 4-3 and 4-18). Common interbeds of fine- to coarse-grained dolomitic sandstone suggest that the tidal flat was also situated very close to the strand line and terrigenous clastic source areas (Barrow arch in the northern Yukon Territory?). Mixed carbonate/terrigenous clastic tidal flats and sabkhas have been recognized along the modern margin of the Red Sea (e.g. Purser et al., 1987; Schreiber et al., 1986) and in the ancient record (e.g. Borer and Harris, 1991; King and Chafetz, 1983; Lomando and Walker, 1991).

Upper Kayak successions at Locations 7 and 8 (Figure 4-3) consist predominantly of wackestone-packstone parasequences and contain only a few shale-limestone parasequences near the base of the upper Kayak Shale (Figure 4-18). Carbonate lithologies near the tops of these parasequences contain abundant (up to 25 to 30% locally) silt- and sand-sized detrital quartz. This suggests deposition in shallow-water, marine settings that were also situated relatively close to terrigenous clastic sources (possibly the Barrow arch).

Paleogeographic relations between the thick acyclic dolomudstone succession at Location 9 and the shoal complex to the north are unknown due to Cenozoic uplift and erosion of the intervening area (Figures 4-3, 4-17, and 4-20). These successions may originally have been part of one large buildup, or may represent two separate buildups.

CONTROLS ON KAYAK-LISBURNE TRANSITION

Many factors influenced the Kayak-Lisburne terrigenous clastic-to-carbonate transition in the northeastern Brooks Range, but the most important were tectonic setting, climate, and possibly a second-order eustatic sea-level rise. In this section, we discuss the significance of each factor in the elimination of terrigenous clastic depositional systems and subsequent establishment an extensive shallow-water carbonate ramp (Lisburne Group).

The Carboniferous Endicott Group in the northeastern Brooks Range was deposited in a rift-flank, upland region landward of the tectonic hinge zone (LePain et al. in review). Prior to latest Tournaisian time, fluvial incision had produced up to 128 m of local topographic relief. Fluvial and marginal-marine successions of the Kekiktuk Conglomerate and marginal-marine successions of the lower Kayak Shale were deposited in incised paleovalleys and eliminated most local relief. As transgression continued, marginal- and shallow-marine deposits of the middle Kayak Shale gradually onlapped and blanketed remnant local paleotopographic highs. Deposition of these units combined with slow subsidence of the rift-flank resulted in an extensive low-relief, south-sloping surface that became increasingly isolated from terrigenous clastic source areas.

The northeastern Brooks Range and most of northern Alaska was situated in a humid climatic zone during the Early Carboniferous (Ravn, 1991, 1992; Utting, 1990, 1991a, 1991b). Ravn (1991, 1992) and Witzke and Heckel (1988) also suggest a relatively low paleolatitude for northern Alaska during this time. Within this climatic context, terrestrial settings throughout the region must have been subjected to intense chemical weathering. The fine-grained nature of the Kayak Shale and abundant organic material within it, combined with its regional extent support a humid climatic setting with intense chemical weathering (e.g. Potter et al., 1980). Also, the paucity of plagioclase feldspar and absence of potassium feldspar in the Kekiktuk Conglomerate in the vicinity of the Devonian Okpilak batholith (LePain, unpublished data; Reed, 1968) support a humid climatic setting.

Humid climatic conditions combined with a low paleolatitude for northern Alaska during the Early Carboniferous resulted in intense weathering, gradual reduction of local topographic relief in the rift-flank region, and a decrease over time in the supply of terrigenous clastic sediment (also partly the result of transgression). Sediment derived from weathering processes in the northeastern Brooks Range provided much of the detritus for the Middle Devonian-Lower Carboniferous terrigenous clastic wedge to the south and southwest (Anderson and Wallace, 1991; Nilsen et al., 1980, 1981) and served as a source of sediment for the Endicott Group in the northeastern Brooks Range (LePain and Crowder, 1992b; Nilsen et al., 1981; Nilsen, 1981) after relative sea-level rise and associated regional transgression initiated deposition in latest Tournaisian time. Intense weathering gradually resulted in reduction of local relief and elimination of terrigenous clastic source areas. Gradual elimination of source areas combined with relative sea-level rise and flooding of the rift-flank region resulted in widespread shale deposition and, eventually, local colonization of the muddy substrate by carbonate-producing organisms during upper Kayak deposition (late Visean). This trend ultimately resulted in establishment of an extensive carbonate ramp.

Eustatic sea-level rise probably contributed to the increasing isolation from terrigenous clastic source areas throughout Kayak deposition. Hallam (1984) constructed a second-order eustatic sea-level curve for pre-Quaternary Phanerozoic time that shows a rise that began in latest Late Devonian time and continued throughout the Early Carboniferous (to the Mississippian-Pennsylvanian boundary). Relative sea-level rise recorded in the Endicott Group from the northeastern Brooks Range may reflect the combined affects of subsidence and a second-order eustatic sea-level rise. The net result was to flood the rift-flank region over a relatively short period of time and establish marine conditions in which carbonate-producing organisms could begin to colonize. Terrigenous clastic input continued throughout upper Kayak deposition and locally formed volumetrically significant accumulations (Locations 2, 9, and 14 on Figure 4-3), but generally decreased in volume on a regional scale.

It is uncertain what mechanisms operated during upper Kayak deposition to produce the small-scale terrigenous clastic-to-carbonate transitions recorded in the meter-scale parasequences. Parasequences are widespread in the upper Kayak Shale and more detailed sampling (0.5 m sample interval) may reveal cyclicity within successions now classified as acyclic. Although Bowsher and Dutro (1957) did not present graphic columnar sections for the Kayak Shale at its type locality in the central Brooks Range, it is apparent from their description that the upper 60 to 70 m of the Kayak Shale constitute a repetitive succession of argillaceous limestone and shale. Thus, it appears that repetitive successions of meter-scale parasequences may dominate the organization of the upper Kayak Shale on a regional scale. However, the lack of detailed biostratigraphic zonation for the upper Kayak Shale in the northeastern Brooks Range and elsewhere precludes correlation of widely spaced measured sections and rigorous investigation of the mechanism(s) that controlled formation of meter-scale parasequences (e.g. Plint et al., 1992).

High-frequency eustatic sea-level fluctuations resulting from the waxing and waning of glaciers in the southern hemisphere (Milankovitch cycles; Fischer, 1986) may provide a viable mechanism for meter-scale cyclicity in the upper Kayak Shale, although this is only speculation. Limited glaciation has been documented in Brazil during early to middle Visean time (Veevers and Powell, 1987). The age of the upper Kayak Shale ranges from at least early middle Visean (Mamet's zone 12, late early Meramec; Mamet and Armstrong, 1972) to middle late Visean (late Meramec-early Chester; Krumhardt and Harris, 1993, personal communication) and overlaps the interval of Brazilian glaciation. Limited continental glaciation, such as affected Brazil in the Visean, may be capable of causing high-frequency eustatic sea-level fluctuations (Grotzinger, 1986). Detailed biostratigraphic data and information on the organization of the Kayak Shale from widely spaced locations - i.e. across the Brooks Range and North Slope subsurface - are required before a rigorous analysis of cyclicity in the upper Kayak can be carried out. Until regional data of this sort are available, other allocyclic (tectonics) and autocyclic mechanisms cannot be ruled out.

CONCLUSIONS

1. Eight lithofacies have been recognized in the upper Kayak Shale, which combine to form meter-scale shale- and carbonate-dominated parasequences and acyclic successions. The type of parasequence and acyclic succession reflects its paleogeographic position with respect to the strand line and terrigenous clastic source areas.

2. Shale-dominated parasequences begin with dark gray and black shale and pass gradually upsection either into argillaceous dolomitic sandstone with *Zoophycos* burrows or into argillaceous skeletal limestone. These parasequences record progressive shoaling above an anaerobic bottom-water layer in restricted-platform

settings. Carbonate-dominated parasequences lack a basal shale, begin with pelmatozoan lime mudstone/wackestone, and pass gradually upsection into pelmatozoan packstone/grainstone. These parasequences record progressive shoaling in open-platform settings.

3. Acyclic packstone successions consist largely of argillaceous spiculitic packstone and record deposition below fairweather wave-base in marginally restricted platform settings. Acyclic grainstone-fossiliferous grainstone successions consist of interlaminated pelmatozoan grainstone and sandy (quartz) grainstone and interbedded fossiliferous sandstone, and record deposition above fairweather wave-base on shoals that developed in open-platform settings. Acyclic dolomudstone successions consist of fine-grained dolomite and minor interbedded dolomitic sandstone and spiculitic packstone, and may record deposition in a mixed carbonate/terrigenous clastic tidal-flat setting, or in a subtidal setting below fairweather wave-base.

4. The paleogeographic distribution of parasequences and acyclic successions in the upper Kayak Shale defined two depositional sub-basins separated by the Devonian Okpilak batholith, which formed a subdued regional topographic high during upper Kayak deposition.

5. The western sub-basin was shale-dominated and is filled with shale-dolomitic sandstone parasequences, shale-limestone parasequences, and a few acyclic packstone successions. Shale-dolomitic sandstone parasequences pass gradually

upsection into shale-limestone parasequences, which records northward retreat of the strand line and terrigenous clastic source areas.

6. The eastern sub-basin is carbonate-dominated and is filled with wackestone-packstone parasequences, minor shale-limestone parasequences, and thick acyclic successions of grainstone-fossiliferous grainstone and dolomudstone, which probably record development of an extensive carbonate platform during upper Kayak deposition. Common silt- and sand-sized detrital quartz in parasequences and acyclic successions on the north side of the eastern sub-basin suggest a paleogeographic highrelatively close to the strand line - which was probably just north of Leffingwell Ridge (Barrow arch ?). Abundant silt- and sand-sized detrital quartz in dolomudstone successions on the southeast side of the eastern sub-basin suggests a source area to the east (possibly the Barrow arch in the northern Yukon Territory).

7. Regional stratigraphic relations suggest that anaerobic conditions recorded in dark gray to black shale of the Kayak developed from a steady supply of terrestrial plant material and restricted circulation due to deposition of coeval carbonate sediment (Lisburne Group) to the south.

8. Subsidence of the rift-flank region during the early drift phase of passive continental margin evolution combined with a second-order eustatic sea-level rise resulted in rapid transgression. The low-latitude and humid climatic setting caused intense chemical weathering and production of large volumes of terrigenous clastic mud. These influenced the overall transition from terrigenous clastic-dominated to

carbonate-dominated environments recorded in the Endicott and Lisburne Groups, respectively.

9. It is uncertain what mechanisms operated to produce the small-scale terrigenous clastic-to-carbonate transitions recorded in the meter-scale parasequences. High-frequency glacioeustatic sea-level fluctuations resulting from the waxing and waning of glaciers in Brazil during the Visean could have influenced deposition of parasequences in the upper Kayak Shale. Detailed biostratigraphic data from the upper Kayak Shale are not available, so other allocyclic and autocyclic mechanisms cannot be ruled out.

CHAPTER 5: CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

CONCLUSIONS

1. In the range-front region of the northeastern Brooks Range, Alaska, the Endicott Group overlies a regional angular unconformity and forms the basal part of the Lower Carboniferous to Lower Cretaceous Ellesmerian sequence. In this region the Endicott Group is latest Tournaisian to late Visean in age and consists, in ascending order, of the fluvial to marginal-marine Kekiktuk Conglomerate and marginal- to shallow-marine Kayak Shale.

2. In the range-front region, fluvial incision occurred prior to latest Tournaisian time, and was followed in latest Tournaisian to earliest Visean time by fluvial deposition within incised paleovalleys due to relative sea-level rise.

3. The sub-Mississippian erosion surface was marked by local erosional relief of only 10's of meters to approximately 200 meters. Six depositional units have been recognized in the Kekiktuk Conglomerate that collectively record progressive infilling of the modest erosional relief on the sub-Mississipian unconformity. The basal depositional units of the Kekiktuk Conglomerate (units A and B) were deposited in relatively steep-sided paleovalleys that were steep enough locally to promote debris flows and were 100's of meters to a few kilometers wide. Onlap relations observed for unit C and regional thickness variations in units C, D, and E indicate that they were deposited in broad paleovalleys a few kilometers to 10's of kilometers wide and had

lower side slopes than recorded in underlying units (A and B). Unit F was deposited above interfluvial highs as a thin fluvial to marginal-marine transgressive veneer.

4. The limited thickness, widespread but discontinuous distribution, and organization of the Kekiktuk Conglomerate (fining-upward megasequence), combined with its stratigraphic position above a regional angular unconformity and below marginal- and shallow-marine shales, suggest deposition in an upland region landward of the tectonic hinge zone on a passive continental margin.

5. The Kekiktuk is a transgressive fluvial deposit at the base of a transgressive marine succession. Fluvial systems are controlled by base-level and for many systems, such as the Kekiktuk Conglomerate, the ultimate base-level is sea-level. Relative sea-level rise initiated Kekiktuk deposition in incised paleovalleys. Relative sea-level rise caused stream equilibrium profiles to shift upward and landward, thereby creating the accommodation space for fluvial sedimentation. Thus, the most important regional control on deposition of the Kekiktuk Conglomerate was relative sea-level rise and the inital phase of the Early Carboniferous transgression in the range-front region of the northeastern Brooks Range was a non-marine depositional episode. Transgressive successions are usually considered to consist entirely of marginal-marine and marine rocks. This makes the transgressive interpretation for the Kekiktuk Conglomerate unusual. Transgressive fluvial successions are probably more common than has been recognized in rift-flank settings.

6. The Kayak Shale is divided into three informal members: 1) the lower Kayak consists primarily of black to dark gray shale and silty shale, with minor sandstone and skeletal carbonate rocks, 2) the middle Kayak consists of black to dark gray siltstone, silty shale, and fissile shale, with rare sandstone and granule/pebble conglomerate near its base, and 3) the upper Kayak, which consists of black to dark gray silty shale, shale, and a variety of skeletal and non-skeletal carbonate lithofacies arranged in meter-scale parasequences and acyclic successions.

7. The lower Kayak Shale is limited to stratigraphic positions above relatively thick valley-filling fluvial successions of the Kekiktuk Conglomerate, which suggests that its distribution was controlled by paleotopographic relief on the sub-Mississippian unconformity. The close association with valley-filling fluvial successions combined with the character of the lower Kayak suggests deposition in a barred estuarine system that was established when the distal parts of paleovalleys were flooded during transgression.

8. Palynologic samples collected from the Kayak Shale indicate that the northeastern Brooks Range was situated in a humid climatic zone during latest Tournaisian to Visean time. Widespread but thin coal in the Kekiktuk Conglomerate and abundant terrestrial plant remains in the Kayak Shale are consistent with this interpretation.

9. The character of the Kekiktuk Conglomerate in the range-front region suggests that parts of the terrestrial coastal zone and some valley bottoms were heavily vegetated. Plant material that was not decomposed or preserved in terrestrial soils was eventually

transported into marginal- and shallow-marine environments. Based on color (dark gray to black) and total organic carbon content (TOC values from 0.8 to 7.94 wt. %), the lower, middle, and some of the upper Kayak Shale was deposited in marginal- and shallow-marine environments characterized by anaerobic to dysaerobic bottom-water layers. Abundant woody and coaly plant fragments in all palynologic samples collected from the Kayak Shale suggest that oxygen-deficient bottom-water conditions were at least partly the result of a steady, high influx of terrestrial plant material into marginal- and shallow-marine environments. Coeval carbonate sedimentation in the Lisburne Group farther south may have contributed to oxygen depletion by restricting water circulation on the shelf.

10. Eight lithofacies have been recognized in the upper Kayak shale, which combine to form meter-scale parasequences and thick acyclic successions. The stratigraphic and geographic distribution of parasequences and acyclic successions in the upper Kayak Shale defines two sub-basins separated by the Devonian Okpilak batholith. The batholith remained emergent throughout most of Kayak deposition.

11. The western sub-basin is shale-dominated and filled with shale-dolomitic sandstone and shale-limestone parasequences, and minor acyclic spiculitic packstone successions. Parasequences record shoaling-upward successions that aggraded/prograded to depths above an anaerobic to dysaerobic bottom-water layer. Spiculitic packstone records small sponge buildups that colonized the muddy substrate and indicates deposition in marginally dysaerobic settings. Subtle topographic highs on the muddy bottom may have extended above the anaerobic

bottom water layer to shallower, less oxygen-deficient water layers, thereby facilitating initial colonization attempts by sponges and other carbonate-producing organisms. The well-known Sadlerochit high and, probably, the Okpilak batholith supplied abundant argillaceous sediment and relatively minor silt- and sand-sized sediment to the western sub-basin. Abundant argillaceous sediment resulted in turbid water conditions over much of the western sub-basin. This made the setting less favorable for carbonate production and promoted development of smaller buildups within a shale-dominated "sea".

12. The eastern sub-basin is carbonate-dominated and filled with wackestone-packstone parasequences, minor shale-limestone parasequences, and thick acyclic successions of grainstone/sandy grainstone, and dolomudstone. Common silt- and sand-sized detrital quartz in parasequences and acyclic successions on the northern side of the sub-basin suggest a paleogeographic position relatively close to the strand line and terrigenous clastic sources, which were probably situated just north of Leffingwell Ridge (possibly the south flank of the Barrow arch). Abundant silt- and sand-sized detrital quartz in dolomudstone successions on the southeastern side of the eastern sub-basin suggests a terrigenous clastic source area to the east (possibly a continuation of the Barrow arch in the northern Yukon Territory). Terrigenous clastic sediment supplied to the eastern sub-basin was dominated by silt- and sand-sized material. Coarser-grained sediment would have settled out of suspension over relatively short periods of time. As a result, clear-water conditions were common in the eastern sub-basin, which were more favorable for carbonate production and promoted larger carbonate buildups.

13. Deposition in a slowly subsiding rift-flank region with a low regional paleoslope toward the south, combined with second-order sea-level rise, resulted in rapid northward transgression. The low-latitude position for northern Alaska during Early Carboniferous time combined with northeastern Alaska's position in a humid climatic zone resulted in intense chemical weathering in terrestrial environments and production of large volumes of terrigenous clastic sediment, especially fine-grained material. All of these factors influenced the transition from terrigenous clastic-dominated to carbonate-dominated environments. In particular, tectonic setting and climate resulted in a gradational terrigenous clastic-to-carbonate transition by providing an abundant supply of terrigenous clastic sediment to both sub-basins.

SUGGESTIONS FOR FURTHER STUDY

1. More detailed study of the internal organization and spatial relationships between depositional units recognized in the Kekiktuk Conglomerate would provide information on its reservoir potential. This could be accomplished by subdividing depositional units into lithofacies assemblages or associations and by applying the method of architectural element analysis (summarized in Miall, 1985) on suitable exposures. If the Kekiktuk Conglomerate is present beneath the coastal plain of the Arctic National Wildlife Refuge (1002 area), the close proximity of exposures of the Kekiktuk Conglomerate in the range front-region to the 1002 area suggest that this information could be critical to detailed reservoir characterization.

2. This study has focused on the Kekiktuk Conglomerate only in the range-front region. Regional studies to the southwest of the range-front region (Echooka anticlinorium west of Juniper Creek) have shown that the Endicott Group becomes finer-grained overall (Clough, 1989, personal communication; Mull, 1990, personal communication). This suggests a slightly different paleogeographic position, probably on the southwestern flank of the upland region that characterizes the northern northeastern Brooks Range. Additional measured sections from this area would provide a more complete understanding of the regional paleogeography.

3. Additional measured sections and lithologic samples of the Endicott Group from the margins of the Okpilak batholith would round out coverage of the Endicott Group in the range-front region. Detailed petrographic analysis (e.g. Dickinson et al., 1979) of sandstone samples collected from the Kekiktuk and Kayak Shale throughout the range-front region and the Echooka anticlinorium, combined with petrographic analysis of a representative suite of samples collected from pre-Middle Devonian rocks throughout the area would allow a detailed evaluation of the relative contributions of local vs. distant sources of terrigenous clastic sediment in the Endicott Group.

4. Detailed biostratigraphy of the Kayak Shale by sampling carbonate *and* argillaceous lithologies for foraminfera and conodonts is essential before a rigorous analysis of cyclicity in the upper Kayak Shale can be done. This information is necessary for detailed correlation of widely spaced measured sections throughout the range-front region (at the parasequence level). With a detailed biostratigraphic framework, the geographic extent of individual parasequences could be evaluated and factors

controlling their deposition (allocyclic vs. autocyclic mechanisms) could be studied in more detail.

5. Total organic carbon (TOC) analyses from a limited suite of samples from the Kayak Shale combined with the dark gray to black color of the Kayak suggest that it was deposited below an anaerobic to dysaerobic bottom-water layer. This interpretation is based on a number of studies that show a strong correlation between the color of shale, TOC values, and deposition in anaerobic to dysaerobic settings (Hosterman and Whitlow, 1983; O'Brien and Slatt, 1990; Potter et al., 1980; Raiswell et al., 1988; Savoy, 1992). Although relatively rare, high TOC values have been reported from some oxic environments (e.g. Demaison and Moore, 1980), and shale color is not always a reliable indicator of deposition in oxygen-depleted environments (e.g. Hosterman and Whitlow, 1983). More detailed and rigorous study of the Kayak Shale is required before a definitive statement can be made regarding its depositional setting in oxygen-depleted environments. Future efforts should be directed toward collecting a suite of samples from the Kayak Shale throughout the range-front region and analyzing them for TOC and sulfur. Plots of organic carbon vs. sulfur are useful in distinguishing anoxic from oxic settings, however, there is often considerable overlap on these plots between anoxic and oxic settings. The technique outlined by Raiswell et al. (1988; degree of pyritization) is a powerful tool for distinguishing anoxic, dysoxic, and oxic environments and, if combined with organic carbon/sulfur plots, would allow a definitive statement on the oxygen conditions in bottom-water layers during Kayak deposition.

APPENDIX A: LOCATION OF MEASURED SECTIONS

Thirty-one columnar sections were measured in the range-front region of the northeastern Brooks Range, Alaska. Locations of measured sections are presented in Table A-1 and shown on Figure A-1. Measured section numbers that are shown in bold italics are included in appendix F. See Appendix for explanation.

Table A-1 - Location of measured sections acquired during this study. Section numbers that are shown in ***bold italic*** letters are included in appendix F; all other measured sections have been previously released as Public Data Files with the State of Alaska Division of Geological and Geophysical Survey. Location of measured sections are shown by number (left column of table) in Figure A-1 on following page.

LOC. #	SECTION #	QUAD.	Twn., Rng., & Section	LAT. - LONG.
1	89ADL1	Mt. Mich. B-4	T2N, R25E, Sec. 30	69°29'51" N., 146°03'55" W.
2	***89ADL2***	Mt. Mich. B-4	T2N, R25E, Sec. 26	69°30'27" N., 145°54'27" W.
3	89ADL3	Mt. Mich. C-3	T2N, R25E, NE1/4 Sec. 23	69°30'59" N., 145°40'00" W.
4	***89ADL4***	Mt. Mich. B-3	T1S, R27E, SE1/4 Sect. 17, NE1/4 Sect. 20	69°21'00" N., 145°38'20" W.
5	***91ADL1***	Mt. Mich. B-3	T2S, R28E, SW1/4 Sect. 1, NW1/4 Sect. 12	69°17'40" N., 145°16'00" W.
6	***91ADL3***	Mt. Mich. B-3	T2S, R27E, NE1/4 Sect. 2	69°18'00" N., 145°31'00" W.
7	***89ADL5***	Mt. Mich. B-3	T1S, R26E, SW1/4 Sect. 35	69°18'29" N., 145°47'50" W.
8	89ADL6	Mt. Mich. A-4	T2S, R24E, Sect. 36	69°13'30" N., 145°13'18" W.
9	89ADL7	Mt. Mich. A-4	T3S, R26E, NE1/4 Sect. 27	69°09'30" N., 145°48'58" W.
10	***89ADL8***	Mt. Mich. A-3	T3S, R28E, Sect. 29	69°09'30" N., 145°24'52" W.
11	89ADL9	Mt. Mich. A-3	T3S, R29E, NW1/4 Sect. 19	69°10'26" N., 145°13'20" W.
	89ADL10	Mt. Mich. A-3	T3S, R29E, SW1/4 Sect 18	69°10'32" N., 145°10'32" W.

Table A-1 - Continued...

12	90ADL4	Dem. Pt. B-4	T1N, R36E, NW1/4 NE1/4 Sect. 2	69°28'30" N., 143°13'00" W.
13	90ADL5	Dem. Pt. B-4	T1N, R36E, Border of NW & NE1/4 Sect. 3	69°28'20" N., 143°16'00" W.
14	***90ADL6***	Dem. Pt. B-4	T2N, R37E, NW1/4 SE1/4 Sect. 31	69°29'00" N., 143°07'15 W.
15	90ADL7	Dem. Pt. B-3	T2N, R38E, E1/2 of NE1/4 Sect. 16	69°31'50" N., 142°47'00" W.
16	90ADL8	Dem. Pt. B-3	T2N, R38E, N1/2 of SE1/4 Sect. 15	69°31'40" N., 142°45'00" W.
17	90ADL9	Dem. Pt. B-3	T2N, R38E, NE1/4 of SW1/4 Sect. 23	69°30'55" N., 142°44'69" W.
18	***90ADL10***	Dem. Pt. B-3	T2N, R39E, NE1/4 of NE1/4 Sect 12	69°32'57" N., 142°25'30" W.
19	90ADL11	Dem. Pt. B-3	T2N, R39E, NW1/4 of NW1/4 Sect 14	69°32'02" N., 142°30'00" W.
20	***90ADL12***	Dem. Pt. B-1	T1N, R45E, NE1/4 of SE1/4 Sect 28	69°24'50" N., 141°04'30" W.
21	90ADL13	Dem. Pt. B-1	T1N, R45E, NW1/4 of NW1/4 Sect. 29	69°25'00" N., 141°08'20" W.
22	***90ADL14***	Dem. Pt. B-2	T1S, R42E, NW1/4 of NW1/4 Sect. 28	69°19'55" N., 142°00'30" W.
23	***90ADL15***	Dem. Pt. B-2	T1S, R42E, E1/2 of SE1/4 Sect. 19	69°20'05" N., 142°03'50" W.
24	88ADL1	Dem. Pt. B-3	T3S, R39E, SE1/4, NE1/4, Sect. 14, and SW1/4, SW1/4, Sect. 14.	69°10'00" N., 142°34'00" W.
25	WAIC1	Dem. Pt. B-4	T1N, R37E, S1/2, NW1/4, Sect. 1	69°23'00" N, 143°05'00" W.

Table A-1 - Continued...

26	91ADL 4	Dem. Pt. B-4	T1S, R37E, NW1/2 of SE1/4 Sect. 8	69°22'00" N., 147°14'00" W.
	91ADL5	Dem. Pt. B-4	T1S, R31E, SE1/4 of NE1/4 Sect. 8	69°22'00" N., 147°13'50" W.
27	90ADL1	Mt. Mich.	T3N, R31E, SW1/4 of SW1/4 Sect. 5	69°38'05" N, 144°35'00" W.
	90ADL2	Mt. Mich.	T3N, R31E, S1/2 of SE1/4 Sect. 6	69°38'05"N 144°36'00"W.
	90ADL3	Mt. Mich.	T3N, R31E, SE1/4 of SW1/4 Sect. 6	69°38'04"N 144°37'00"

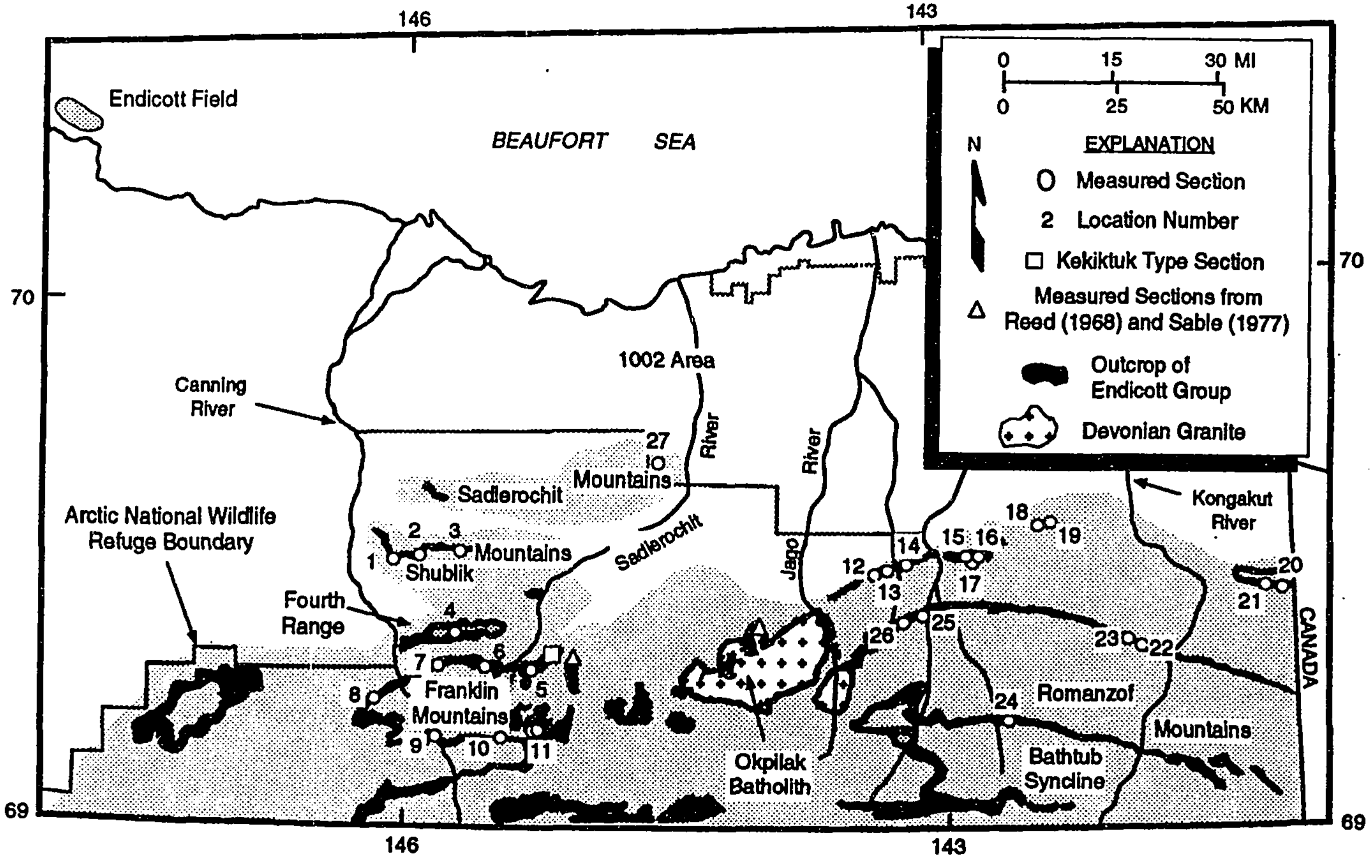


Figure A-1 - Map of the northeastern Brooks Range showing locations of measured sections. Location numbers are keyed to Table A-1. Modified from Bird et al. (1987).

APPENDIX B: PALYNOLOGIC AND CONODONT SAMPLES

A total of 78 palynologic samples were collected from argillaceous rocks in the Endicott Group. All samples processed and picked by Dr. John Utting of the Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, Calgary, Alberta. Palynologic sample reports are available to the public from the Geological Survey of Canada: data from samples collected during the 1989 field season (Mt. Michelson quadrangle) are reported in No. 2-JU-90; data from samples collected during the 1990 field season (Demarcation Point quadrangle) are reported in No. 5-JU-91; and data from the 1991 field season (Mt. Michelson and Demarcation Point quadrangles) are reported in No. 7-JU-91. Table B-1 is a summary of data presented in these reports, including thermal alteration indices for each sample. Table B-2 correlates thermal alteration indices derived from palynomorphs with CAI data from conodonts and vitrinite reflectance data from organic material.

A total of 24 conodont samples were collected from the Kayak Shale and basal Lisburne Group (Alapah Limestone and Wachsmuth Limestone) across the study area (Figure A-1). Samples collected during the 1989 field season (sample numbers begin with 89ADL) were were collected from locations in Mt. Michelson quadrangle, and were processed and picked for conodonts by Dr. Anita Harris of the U.S. Geological Survey in Reston, Virginia. Samples collected during the 1990 and 1991 field seasons were collected from Mt. Michelsone and Demarcation Point quadrangles, and were processed and picked by Andrea Krumhardt of the University of Alaska, Fairbanks, Alaska. Identifications were later verifi.ed by Dr. Anita Harris. Conodont sample reports are available to the public from the U.S. Geological Survey, Reston, Virginia, shipment #O-91-12. Table B-3 is a summary of data presented in these reports.

Table B-1 - Summary table of data from palynologic samples collected from the Endicott Group. Sample collected from the Kekiktuk Conglomerate are underlined (sample number).

LOCATION NUMBER	SAMPLE NUMBER	AGE/ IDENTS.	TAI	OTHER MATERIAL	DESCRIP-TION
1	89ADL1-1.1	No palynomorphs	-	Black woody, coaly and exinous frags.	-
	89ADL1-74.8	Visean (V1-early V3)	4	Woody , coaly, and minor exinous frags.	Humid
2	89ADL2-41.0	No palynomorphs	4	Woody, coaly, and minor amounts of exinous and amorphous frags.	-
	89ADL2-84.0	No palynomorphs	4	Woody, coaly, and minor amounts of exinous and amorphous frags.	-
3	89ADL3-1.5	No palynomorphs	4	Woody, coaly, and minor amounts of exinous and amorphous frags.	-
4	89ADL4-9.2	No palynomorphs	5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL4-45.5	No palynomorphs	5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL4-56.4	No palynomorphs	5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL4-84.0	Visean	4/5	Woody, coaly, and minor amounts of exinous frags.	Humid
	89ADL4-100.1	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-

Table B-1 - Continued...

	89ADL4-109	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL4-123	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL4-170.6	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-
6	91ADL3-2.0	No palynomorphs	5?	Woody and coaly frags.	-
	91ADL3-8.8	No palynomorphs	5?	Woody and coaly frags.	-
	91ADL3-17.6	No palynomorphs	5?	Woody and coaly frags.	-
	91ADL3-32.4	No identifiable palynomorphs	5	Woody and coaly frags, rare black spores.	-
	91ADL3-39.5	No palynomorphs		Coal sample.	-
	91ADL3-51.0	No palynomorphs	5?	Woody, coaly, and minor amounts of exinous frags.	-
	91ADL3-94.4	No palynomorps		Coal sample	-
	91ADL3-94.5	No identifiable palynomorphs	5	Woody and coaly frags, rare vitreous black spores.	-
	91ADL3-113.9	No identifiable palynomorphs	5	Woody, coaly, and exinous frags, common vitreous black spores.	-
	91ADL3-118	*Verrucosissporites sp.*	5	Woody and coaly frags, common vitreous black spores.	-

Table B-1 - Continued...

	91ADL3-190	No palynomorphs	-	Woody and coaly frags.	-
	91ADL3-220	*Cingulizonates bialatus*	5	Woody, coaly, and rare exinous frags.	-
	91ADL3-254	*Cingulizonates bialatus*	5	Woody, coaly, and rare exinous frags.	-
	91ADL3-332	No identifiable palynomorphs	5	Woody, coaly, and exinous frags, circular spores.	-
7	89ADL5-45	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags. Scolecodonts.	Marine
	89ADL5-62.2	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-
8	89ADL6-16.4	Visean	4/5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL6-84.8	Non diagnostic	4/5	Woody, coaly, and minor amounts of exinous frags.	Humid
9	89ADL7-33.0	No palynomorphs	4/5	Woody and coaly fragments.	-
	89ADL7-61	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous fragments.	-
	89ADL7-160.2	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-
10	89ADL8-5.5	No palynomorphs	4/5	Woody, coaly, and minor amounts of exinous frags.	-
	89ADL8-75	No palynomorphs	4.5	Woody, coaly, and minor amounts of exinous frags.	-

Table B-1 - Continued...

	89ADL8-92	Non recognizeable	4/5	Woody and coaly frags. Rare circular spores and scolecodonts.	-
	89ADL8-134.6	Non diagnostic	4/5	Woody and coaly frags.	Humid
12	90ADL5-74	No palynomorphs	4	Woody and coaly frags.	-
17	90ADL9-9	Visean (V1-early V3?)	4	Woody, coaly, and minor amounts of exinous frags.	Terrestrial, humid
19	90ADL10-5	Visean	4	Woody, coaly, and minor amounts of exinous frags.	-
	90ADL10-280	Visean	4	Woody, coaly, and minor amounts of exinous frags.	Terrestrial - nearshore marine
21	90ADL12-12	Visean	5	Woody, coaly, and minor amounts of exinous frags. Black spores common.	Terrestrial
	90ADL12-25	Early Carboniferous	5	Woody, coaly, and minor amounts of exinous frags. Black spores common.	Terrestrial
	90ADL12-43	No palynomorphs	5	Woody, coaly, and amorphous frags.	-
	90ADL12-51	No palynomorphs	5	Woody, coaly, and minor amounts of exinous frags. Scolecodont.	Nearshore marine
	90ADL12-60	Early Carboniferous	5	Woody, coaly, and rare exinous frags.	Terrestrial

Table B-1 - Continued...

	90ADL12-85	Early Carboniferous	5	Woody, coaly, and rare exinous frags.	Terrestrial
	90ADL12-146	No palynomorphs	5	Woody, coaly, and rare exinous frags.	-
22	90ADL14-40	No palynomorphs	5	Woody, coaly, and rare exinous frags.	-
23	90ADL15-11	No palynomorphs	-	Woody and coaly frags.	-
	90ADL15-31.5	No palynomorphs	5	Woody, coaly, and rare exinous frags.	-
23	90ADL15-52	Visean (V1-early V3)	5	Woody, coaly, and rare exinous frags.	Terrestrial, humid
	90ADL15-125	Visean	5	Woody, coaly, and rare exinous frags. Scolecodonts.	Nearshore marine, humid
	90ADL15-133	Visean	5	Woody and coaly frags. Black spores common. Scolecodonts.	Nearshore marine, humid
	90ADL15-144	Visean (V1-early V3)	5	Woody and coaly frags. Black spores common. Scolecodonts.	Nearshore marine, humid
	90ADL15-173	Visean (V1-early V3)	4/5	Woody and coaly frags. Black spores common. Scolecodonts.	Nearshore marine, humid
	90ADL15-185	Visean (V1-early V3)	4/5	Woody and coaly frags. Black spores common. Scolecodonts.	Nearshore marine, humid
24	91(88)ADL2-2	l. Toum-e. Visean	4/5	Woody and coaly frags.	-
26	91ADL4-4.4	No palynomorphs	-	Little organic matter; some woody and coaly frags.	-

Table B-2 - Correlation table for CAI, TAI, and vitrinite reflectance values. Adapted from Utting et al. (1989).

Thermal Alteration Index	Conodont Color Alteration Index	Vitrinite Reflectance	Zones of Petroleum Generation and Destruction (amorphous organic matter)
1			
	1		
1+			
		0.3	
		0.4	
2-			
		0.5	—— Oil "Birth" Line ——
2			
		0.6	
	1.5	0.9	Peak Oil Generation
2+			
		1.0	Peak Wet Gas Generation
3-	2.0	1.2	Peak Dry Gas Generation
	2.5	1.35	—— Oil "Death" Line ——
3	3.0		
	3.5	1.5	
3+			
	4.0		
4-	4.5	2.0	—— Wet Gas Floor ——
		2.2	
4			
		3.0	— Dry Gas Preservation Limit —
		3.5	
	5.0		
5			
	6.0	4.0	
		5.0	

Table B-3 - Summary table of data from conodont samples collected from Kayak Shale and Alapah Limestone in the northeastern Brooks Range.

LOCATION NUMBER	SAMPLE NUMBER	AGE/ IDENTS.	CAI	OTHER MATERIAL	INTERPRE-TATION
2	89ADL2-0.0	early E. Ordovician	4	-	Platformal, warm, norm.-marine to partly restricted, shallow water.
3	89ADL3	late M.-L. Ordovician	4	-	Indeterminant, postmort. hydraul. trans., shallow water, intermit. high energy.
	89ADL3-35.2	Probable Late Meremecian	4	-	Indeterminant, postmort. hydraul. trans., shallow, warm water, partly restricted.
4	89ADL4-138.6	No conods. rec.	-	Abundant robust ichthyoliths (fish teeth and dermal plates.	-
	89ADL4-175.2	No conods. rec.	-	-	-
6	91ADL3-209.0	Late Miss. to Early Penn.	?	Abundant phosphatic bioclasts and pyrite, common ichthyoliths, possibie glauconite.	Indeterminant.
9	89ADL7-58	Probably Miss.	5	-	Indeterminant, postmort. hydraul. trans. in relatively high energy environ.
9	89ADL7-160.4	Probably Miss.	5	Common ichthyoliths	Indeterminant, probably high energy, partly restricted.

Table B-3 - Continued...

10	89ADL8-118.9	No conods. rec.	-	-	-
	89ADL8-203.0	Probably Miss.	5	-	Indeterminant, postmort. hydraul. trans.
	89ADL10-61.95	No conods. rec.	-	-	-
14	90ADL6-174.0	Osagean to Chesterian	4.5-5	Common ichthyoliths, 2 phosphatic bioclasts.	Indeterminant.
	90ADL6-231.4	upper Meramecian	5-6	Minor ichthyoliths.	Indeterminant.
	90ADL6-296.0	upper Meramecian to lower Chesterian	5.5-6.5	Abundant phosphatic bioclasts.	Indeterminant, postmort. hydraul. trans.
15	90ADL7-168.0	upper Meramecian to lower Chesterian	5.5-6	Abundant phosphatic bioclasts and pyrite.	Indeterminant.
16	90ADL8-141.0	No conods. rec.	-	Common pyrite, hematite, and dolomite.	-
	90ADL8-155.0	No conods. rec.	-	Rare ichthyoliths, abundant pyrite.	-
17	90ADL9-63.0	No conods. rec.	-	Abundant dolomite, minor pyrite and phosphatic bioclasts.	-
	90ADL9-97.0	upper Meramecian to lower Chesterian	5.5	Phosphatic bioclasts, abundant pyrite.	Indeterminant.
19	90ADL10-159.8	upper Meramecian	4-6	Hematite, pyrite, minor dolomite.	Indeterminant.
	90ADL10-191.5	upper Meramecian	4	Abundant glauconite?	Indeterminant.

Table B-3 - Continued...

	90ADL10-248.0	upper Meramecian? Possibly upper Meramecian to lower Chesterian	6	Abundant dolomite.	Shallow open-platform, low-to-moderate energy.
	90ADL10-310.0	No conods. rec.	-	Abundant dolomite and pyrite.	-
20	90ADL12-173.4	upper Meramecian to lower Chesterian	5	Common phosphatized bioclasts.	Indeterminant.
	90ADL12-204.0	Indeterminant	5.5	Common dolomite, pyrite.	Indeterminant.
21	90ADL13-310.0	upper Meramecian to lower Chesterian	6	Abundant dolomite.	Indeterminant.
23	90ADL15-125.6	upper Meramecian to lower Chesterian	5	Abundant pyrite and pyritized bioclasts, common ichthyoliths and phosphatic grains.	Indeterminant.
	90ADL15-393.0	upper Meramecian to lower Chesterian	5-5.5	Abundant phosphatic grains and rare bioclasts.	Indeterminant.
26	91ADL5-148.2	latest Chesterian to lower Atokan	6-6.5	Dolomite and pyrite.	Indeterminant.

APPENDIX C: SANDSTONE MODAL ANALYSES

Twenty eight thin-sections were selected for modal analysis in order to obtain a general estimate of the composition of sandstones in the Kekiktuk Conglomerate and Kayak Shale. Each thin-section was divided into four quadrants of roughly equal area and the composition of grains, matrix, or cement at 75 five locations in each quadrant was recorded. Counting locations were selected by lightly tapping the edge of a slide to change its position on the microscope stage - whatever lie below the cross-hairs in the occular was then counted. Results of modal analyses are summarized in Table C-1 and point counts are in Table C-2.

Table C-1 - Summary of modal data from sandstones in the Endicott Group. Approximately 300 grains counted per thin-section. 14 samples were counted from the Kekiktuk Conglomerate and 14 from the Kayak Shale. Range is shown in parentheses below the mode for each constituent.

CONSTITUENT	KEKIKTUK CGL. Mode (Range)	KAYAK SHALE Mode (Range)
Monocrystalline Quartz	73.4 (32-94)	58.9 (8-88)
Polycrystalline Quartz	8.2 (Trace-18)	9.1 (Trace-23)
Common Chert	2.0 (0-14)	3.8 (0-27)
Argillaceous Chert	4.0 (0-30)	5.4 (0-31)
Radiolarian Chert	Trace	Trace
Rock Fragments	1.0 (0-7)	0.7 (0-4)
Detrital Phyllosilicates	1.0 (0-2)	0.1 (0-2)
Mudstone Intraclasts	Trace	0.3 (0-3)
Matrix	7.3 (0-22)	12.0 (0-30)
Opaques	2.0 (0-8)	4.5 (0-13)
Mafic Grains	Trace	Trace
Siliceous Cement	1.0 (0-7)	0.6 (0-4)
Carbonate Cement	-	0.9 (0-12)
Porosity	1.0 (0-4)	1.2 (Trace-6)

Table C-2 - Point count data. Point counts from 28 thin sections selected from the Kekiktuk Conglomerate and Kayak Shale. 300 counts per thin section where possible. Kekiktuk samples are underlined. Qms = monocrystalline quartz, Qmu = monocrystalline undulose quartz, Qps = Polycrystalline, straight extinction, Qpu = polycrystalline quartz, undulose extinction, Cc = common chert, Ca = cherty argillite, Crd = radiolarian chert, Cch = chalcedonic chert, Phyll = phyllite rock frag., Qtour = quartz-tourmaline rock frag., Rphy = recrystallized phyllitic matrix, Charg = cherty argillite matrix, Md = terrigenous mud matrix, Opaq = opaque grains, Qcem = quartz cement.

Sample	Qms	Qmu	Qps	Qpu	Cc	Ca	Crd	Cch	Phyll	Qtour	Rphy	Charg	Md	Opaq	Qcem
<u>88ADL2-4</u>	81	129	2	15	7	16	-	-	7	-	15	3	5	1	1
<u>89ADL1-1</u>	207	82	-	15	5	10	-	-	-	-	4	-	-	-	7
89ADL1-63	137	74	1	-	11		-	-	-	-	17	7	-	42	14
<u>89ADL2-21</u>	181	81	-	1	1	4	-	-	-	-	-	13	-	4	22
89ADL2-35.8	206	85	2	3	-	-	-	-	-	-	10	-	-	3	13
89ADL4-43.2	125	45	12	5	-	-	-	-	-	-	-	2	-	5	-
89ADL5-63.6	192	22	24	5	-	-	-	-	-	-	2	54	-	22	-
89ADL5-65	100	72	17	4	1	-	-	-	10	-	37	-	2	29	-
89ADL5-C1.5	176	44	21	9	-	-	-	-	-	-	6	34	3	16	-
<u>89ADL6-8</u>	156	111	13	6	-	-	-	-	-	-	-	-	-	2	21
<u>89ADL7-35</u>	109	86	8	-	-	-	-	-	7	-	61	-	1	10	-
<u>89ADL7-37</u>	52	155	1	2	6	18	-	-	-	-	2	18	1	23	1
<u>89ADL9-1.4</u>	26	98	4	29	1	3	-	-	2	1	3	7	-	10	-
<u>89ADL9-3.2</u>	47	128	7	8	1	-	-	-	-	1	23	-	-	2	2
<u>89ADL9-11.3</u>	38	157	1	45	1	4	-	1	17	-	28	-	-	5	-

Table C-2 - Continued...

Sample	Qms	Qmu	Qps	Qpu	Cc
90ADL4-24.5	166	18	20	2	-
90ADL5-43	121	37	26	12	-
90ADL10-15	114	85	9	28	10
90ADL11-51	1	11	1	31	39
90ADL12-2	167	123	3	2	-
90ADL12-13	80	126	-	47	3
90ADL12-29	138	112	2	2	1
90ADL14-45	26	73	4	47	42
90ADL14-60	52	108	1	26	19
90ADL15-4	132	162	4	3	2
90ADL15-16.8	19	60	8	62	24
90ADL15-25	53	154	3	15	16
WAIC-1	59	140	9	27	9

Ca	Crd	Cch	Phyll	Qtour	Rphy	Charg	Md	Opaq	Qcem
2	-	-	2	-	77	-	6	6	-
3	-	-	1	-	85	1	1	5	-
44	-	2	-	-	5	3	-	8	-
46	-	-	-	-	-	4	-	-	-
-	-	-	-	-	8	-	1	3	-
-	-	-	-	-	3	-	45	1	-
-	-	-	-	-	22	-	2	5	1
66	1	3	-	-	19	-	-	2	1
36	-	-	13	-	10	-	19	2	3
-	-	-	-	-	-	-	-	-	6
47	1	1	-	-	9	-	-	32	-
14	-	2	-	-	17	-	1	13	2
11	-	-	18	-	42	-	-	-	-

APPENDIX D: POROSITY AND PERMEABILITY ANALYSES

Selected sandstone samples from the Kekiktuk Conglomerate and Kayak Shale were sent to Core Laboratories for porosity and permeability analyses. The following description of sample processing was provided by Core Laboratories. Results are summarized in Table D-1.

Upon arrival at Core Laboratories' Anchorage facility, the sample bags were removed from their boxes and grouped according to the first two digits of the sample numbers. The samples were then removed from their bags and one plug was drilled from each sample horizontal to the bedding planes (where visible). The plugs were trimmed into right cylinders, numbered, and cleaned by soaking in toulene for a period of 24 hours. Once removed from the toulene, they were dried in a convection oven for 12 hours at 240 degrees F.

Grain density was determined by first measuring grain volume and mass. Grain volume was measured according to Boyle's Law utilizing the Extended Range Helium Porosimeter. Density was then calculated using the equation - grain density = grain mass/grain volume.

Atmospheric porosity was determined after measuring bulk volume by mercury displacement at ambient conditions. Grain volume was measured as described in the preceeding paragraph. Porosity was calculated using the equation - Porosity = ((bulk volume - grain volume)/bulk volume) x 100.

Horizontal permeability was measured in a Hassler type core holder at a confining pressure of 400 lbs in^2. Permeability calculations were performed as defined by Darcy's equation for compressible fluids - K = [((atmospheric pressure x gas viscosity x 1000)/(pressure differential) x (mean pressure))] x ((flow rate) x ($length^2$)/bulk volume).

Table D-1 - Porosity and permeability data from selected sandstones in the Endicott Group.

Sample	Permeability to Air (md)	Porosity % (Helium)	Grain Density	Description
89ADL1-1.6	0.02	2.5	2.64	Sandstone.
89ADL2-22.0	0.05	1.5	2.64	Sandstone.
89ADL2-35.8	0.01	3.2	2.69	Sandstone, vuggy, bituminous.
89ADL5-C1	0.05	2.5	2.67	Sandstone.
89ADL6-5.2	0.02	1.2	2.66	Conglomerate.
89ADL6-8.0	0.01	1.3	2.64	Sandstone.
89ADL9-1.4	0.03	5.0	2.67	Sandstone.
89ADL9-10.1	0.02	3.3	2.67	Sandstone.
90ADL4-24.5	0.07	1.9	2.70	Sandstone.
90ADL5-43.0	0.06	2.0	2.71	Sandstone, limonitic.
90ADL14-19.0	0.00	0.5	2.68	Mudstone.
90ADL14-45.0	0.15	1.8	2.67	Sandstone.
90ADL15-16.8	0.00	1.8	2.91	Sandstone, limonitic. trace mafic grains and pyrite.
91ADL3-9.2	0.02	0.7	2.66	Sandstone.
91ADL3-45.8	0.03	1.2	2.65	Sandstone.
91ADL3-11.9	0.02	1.1	2.66	Sandstone.
91ADL3-124.6	0.00	0.6	2.67	Sandstone.
91ADL3-245.8	0.02	1.6	2.65	Sandstone.

APPENDIX E: TOTAL ORGANIC CARBON ANALYSES

Nineteen outcrop samples from the Kayak Shale were analyzed for total organic carbon (TOC) by Ellington and Associates, Houston Texas, using the LECO method. Results are summarized in Table E-1. The following description of the LECO method was provided by Ellington and Associates.

This is a method for determing TOC in drill cuttings, conventional and sidewall cores, outcrop samples, and recent sediments. It is applicable to organic samples containing at least 0.01% TOC and up to 100% TOC.

To remove and determing quantitatively the amount of inorganic carbon, a sample is weighed in a porous ceramic leaching crucible and then leached with hot 6N HCL. This provides a measure of inorganic carbon.

The sample remaining in the crucible is then combusted in a Leco induction furnace converting the carbon to CO_2. During combustion, the concentration of gases in a closed loop rapidly becomes homogeneous. Only CO_2 is detected by a solid state infrared detector. During combustion, infrared absorption properti.es of CO_2 in the chamber causes a loss of energy; therefore, a loss in signal results, which is proportional to the concentration of gas. This proportional change is electrically processed to be displayed as percent carbon.

Table E-1 - Results of TOC analyses for the Kayak Shale.

Sample	TOC (wt.%)
89ADL2-41.0	2.55
89ADL2-84.0	2.09
89ADL4-9.2	2.01
89ADL4-45.5	1.26
89ADL4-84.0	2.75
89ADL4-109.0	2.06
89ADL4-123.0	1.82
89ADL4-170.6	3.10
89ADL5-45.0	1.43
89ADL5-62.2	2.25
89ADL6-16.4	1.98
89ADL6-84.8	1.9
89ADL7-33.0	7.94
89ADL7-61.0	1.54
89ADL7-160.2	0.80
89ADL8-5.5	2.26
89ADL8-75.0	1.61
89ADL8-92.0	1.70
89ADL8-134.6	1.65

APPENDIX F: MEASURED SECTIONS

Thirty-one columnar sections were measured in the range-front region of the northeastern Brooks Range, Alaska. Many of these were measured through poorly exposed successions of the Endicott Group. Only measured sections from the best exposed successions of the Endicott Group are included in appendix F (eleven measured sections). All measured sections have been previously released as Public Data Files through the Alaska Division of Geophysical and Geological Surveys in Fairbanks, Alaska (LePain and Crowder, Public Data Files 89-1e, 90-19, 91-11, and 92-5). The format that measured sections were drafted in evolved through the course of the study. As a result, the suite of measured sections includes three different formats. Measured sections are designated in the order in which they were obtained by year, region, geologist's initials, and a number; for example 89ADL1 was measured in 1989 in Alaska by David LePain and it was the first section measured that season. Measured section numbers are shown on each page. All section numbers are keyed to table A-1 and Figure A-1, which contain locations of all thirty-one measured sections. Sample location and type is shown in the "meters/sample" column to the left of the rock type column on measured sections obtained during the 1990 and 1991 seasons. Sample type is designated with a letter as follows: L = lithologic sample, C = conodont sample, and P = palynologic sample. If more than one type of sample was collected at a specific stratigraphic level, the sample types are shown as C/L, L/P etc.

1989 MEASURED SECTION KEY

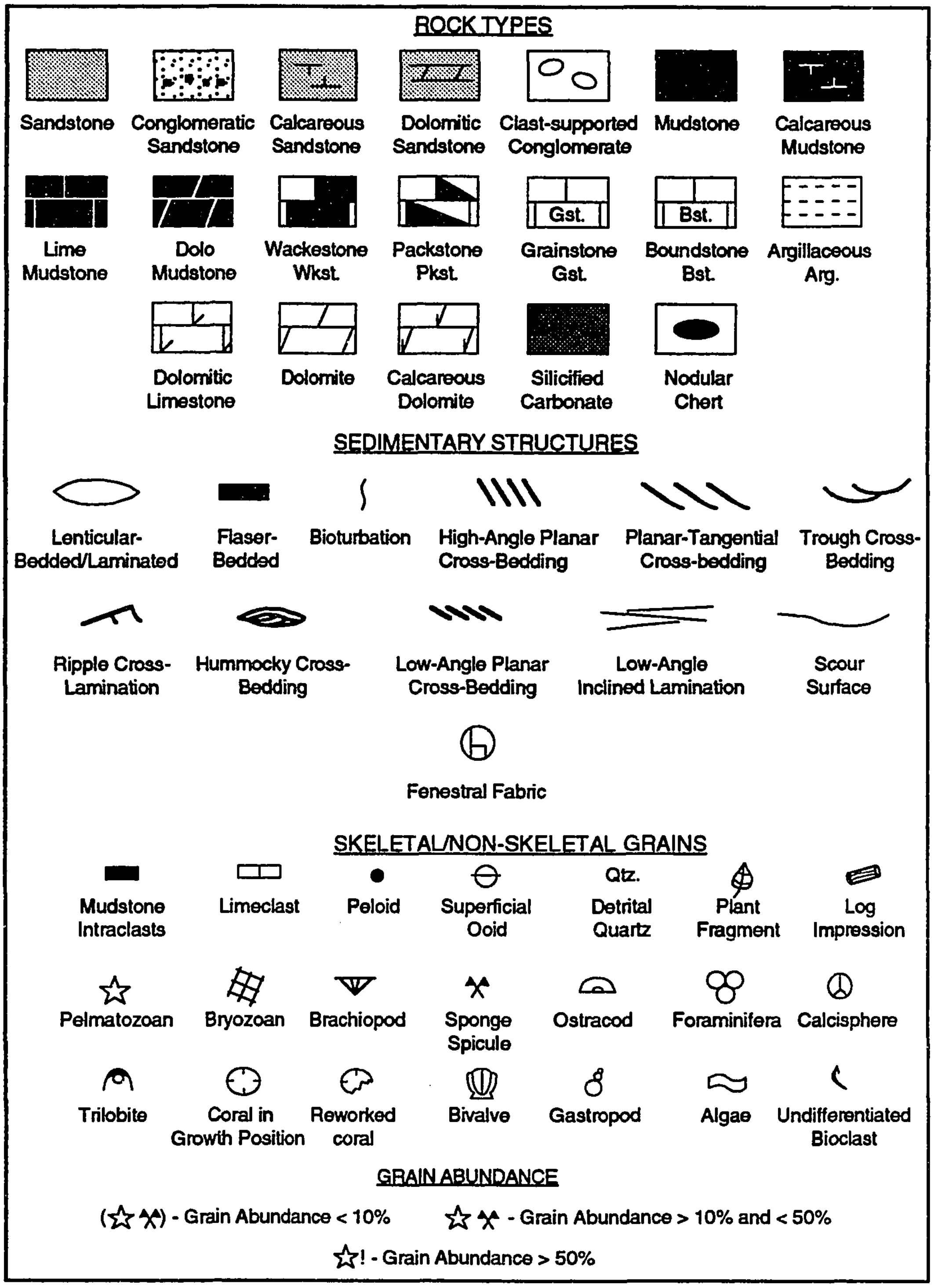
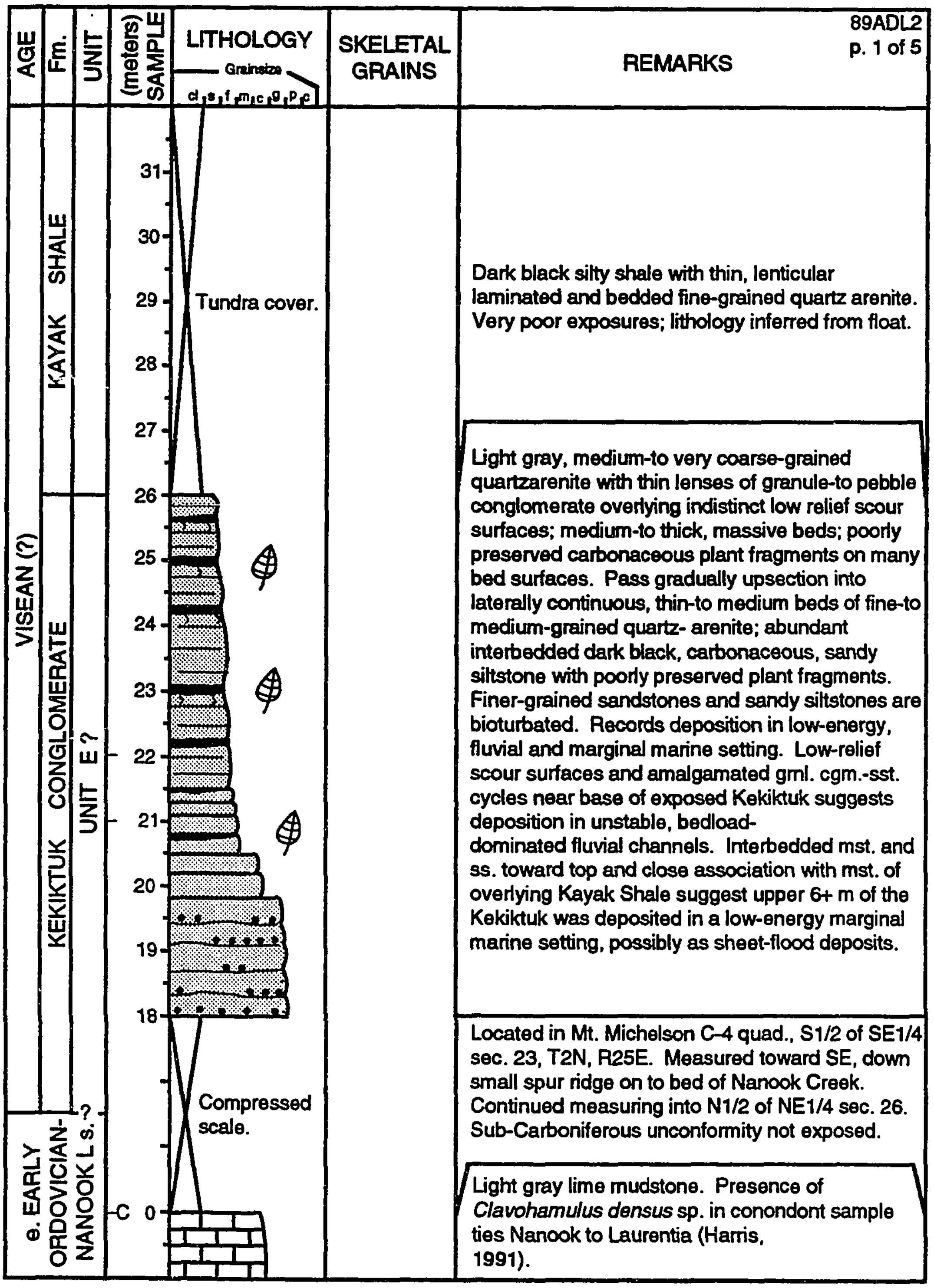
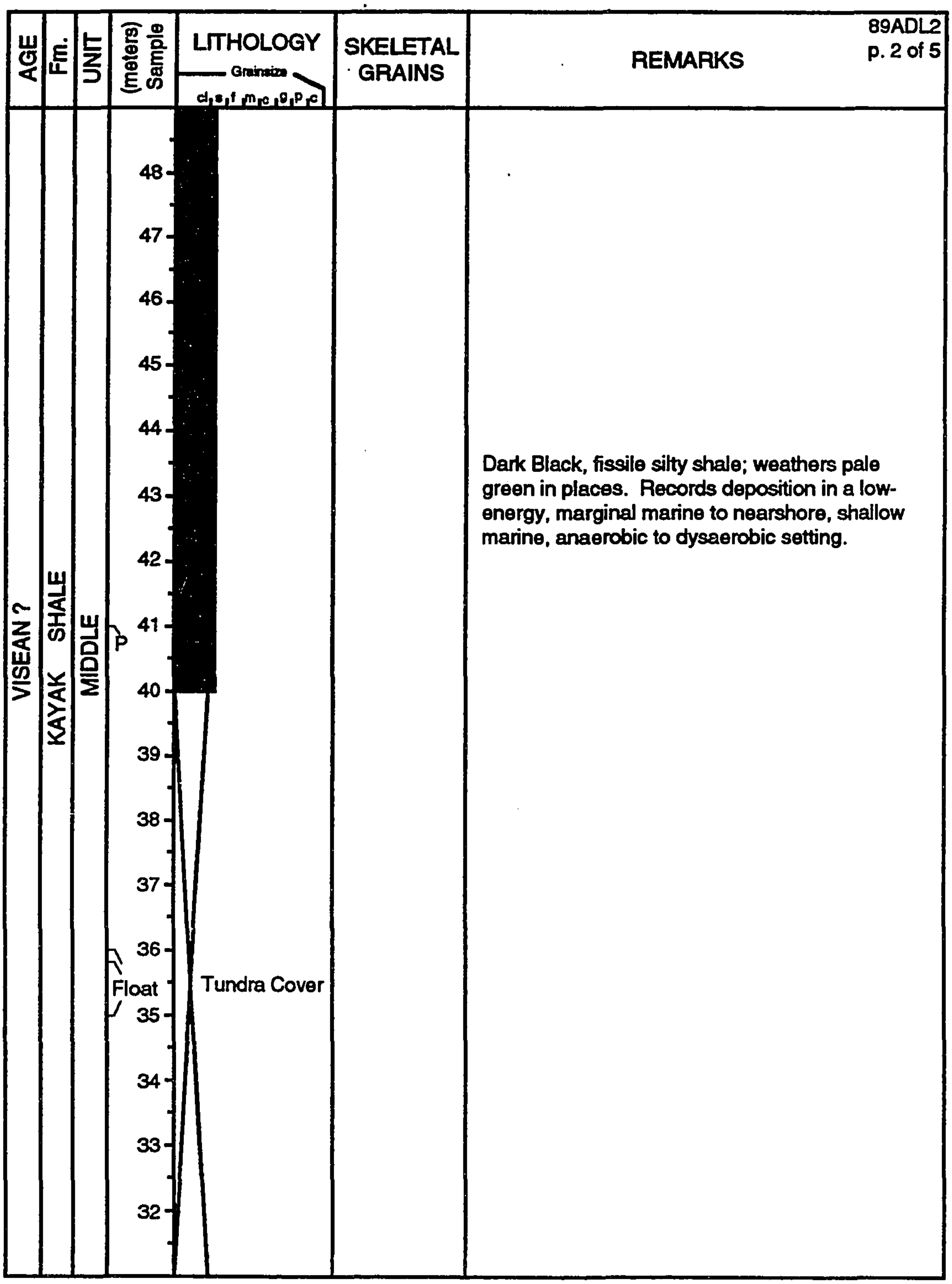
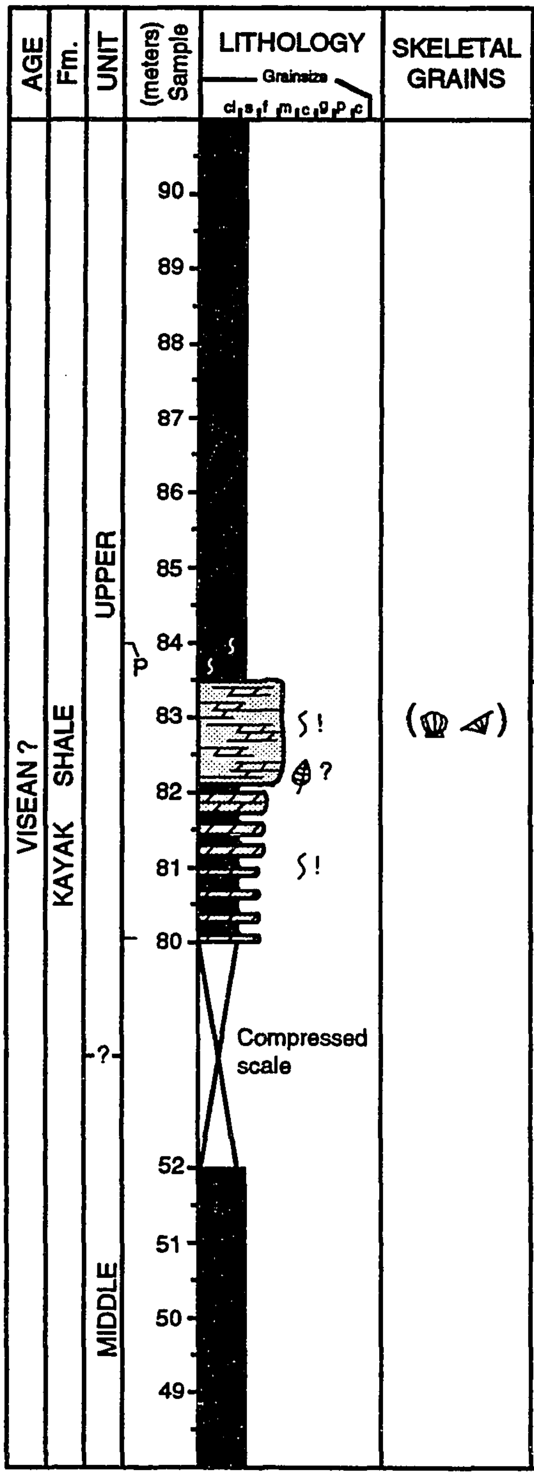


Figure F-1 - Key to symbols used in measured sections obtained during the 1989 field season.


AGE
Fm.
UNIT
(meters)
SAMPLE
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
89ADL2
p. 1 of 5
VISEAN (?)
KAYAK SHALE
KEKIKTUK CONGLOMERATE
UNIT E ?
e. EARLY ORDOVICIAN-
NANOOK Ls.?
31
30
29
28
27
26
25
24
23
22
21
20
19
18
C 0
Tundra cover.
Compressed scale.
Dark black silty shale with thin, lenticular laminated and bedded fine-grained quartz arenite. Very poor exposures; lithology inferred from float.
Light gray, medium-to very coarse-grained quartzarenite with thin lenses of granule-to pebble conglomerate overlying indistinct low relief scour surfaces; medium-to thick, massive beds; poorly preserved carbonaceous plant fragments on many bed surfaces. Pass gradually upsection into laterally continuous, thin-to medium beds of fine-to medium-grained quartz- arenite; abundant interbedded dark black, carbonaceous, sandy siltstone with poorly preserved plant fragments. Finer-grained sandstones and sandy siltstones are bioturbated. Records deposition in low-energy, fluvial and marginal marine setting. Low-relief scour surfaces and amalgamated grnl. cgm.-sst. cycles near base of exposed Kekiktuk suggests deposition in unstable, bedload-dominated fluvial channels. Interbedded mst. and ss. toward top and close association with mst. of overlying Kayak Shale suggest upper 6+ m of the Kekiktuk was deposited in a low-energy marginal marine setting, possibly as sheet-flood deposits.
Located in Mt. Michelson C-4 quad., S1/2 of SE1/4 sec. 23, T2N, R25E. Measured toward SE, down small spur ridge on to bed of Nanook Creek. Continued measuring into N1/2 of NE1/4 sec. 26. Sub-Carboniferous unconformity not exposed.
Light gray lime mudstone. Presence of *Clavohamulus densus* sp. in conondont sample ties Nanook to Laurentia (Harris, 1991).


AGE
Fm.
UNIT
(meters) Sample
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
89ADL2
p. 2 of 5
VISEAN ?
KAYAK SHALE
MIDDLE
P
Float
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
Tundra Cover
Dark Black, fissile silty shale; weathers pale green in places. Records deposition in a low-energy, marginal marine to nearshore, shallow marine, anaerobic to dysaerobic setting.

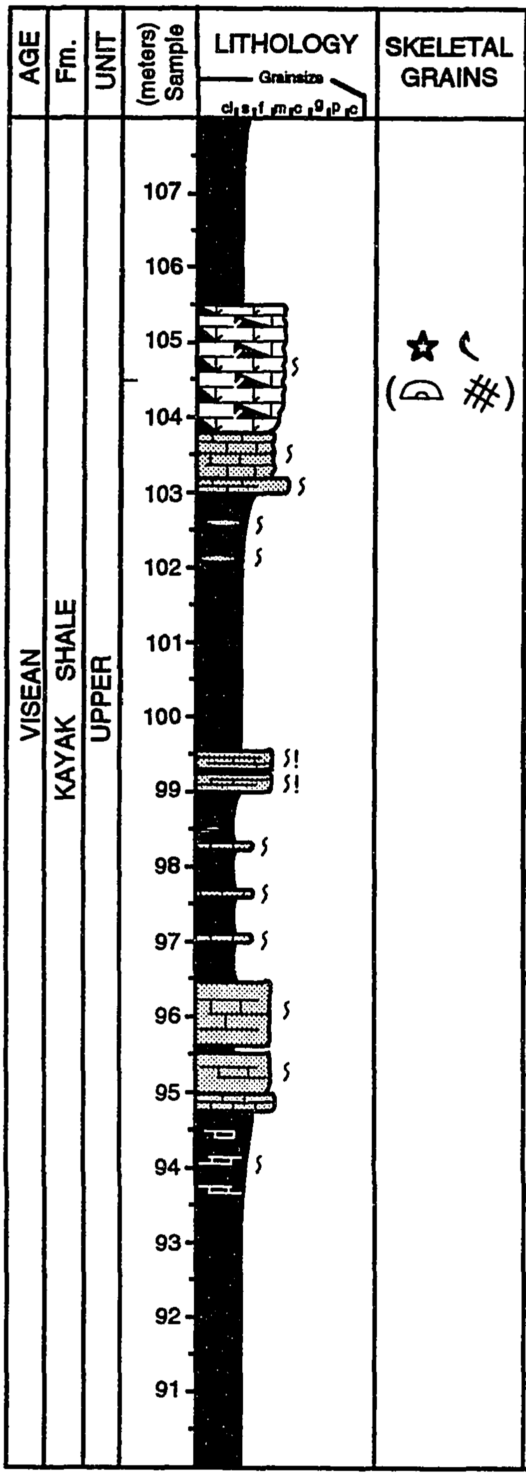
89ADL2
p. 3 of 5



REMARKS

Dark black, organic-rich mst. Records deposition in low-energy, marine, anaerobic to dysaerobic setting.

Dark black, fissile, pyritic mudstone; mudstone passes gradually upsection into interbedded mudstone and silty/sandy macrodolomite. Overlain by dark gray, silty/sandy dolomite with some thinly interbedded carbonaceous mudstone; highly bioturbated with numerous vertical burrows present on bedding surfaces. Shoaling-upward succession deposited in a restricted-platform setting with anaerobic to dysaerobic bottom water conditions. Dolomitic sandstone near top records progradation/aggradation above anaerobic bottom water layer. Terrestrial plant remains and fine- to medium-grained detrital quartz indicate deposition relatively close to the strand line. Sand-sized terrigenous clastic material probably transported by storm-generated currents.



REMARKS — 89ADL2 p. 4 of 5

Black, fissile shale. Restricted-platform setting anaerobic bottom water conditions.

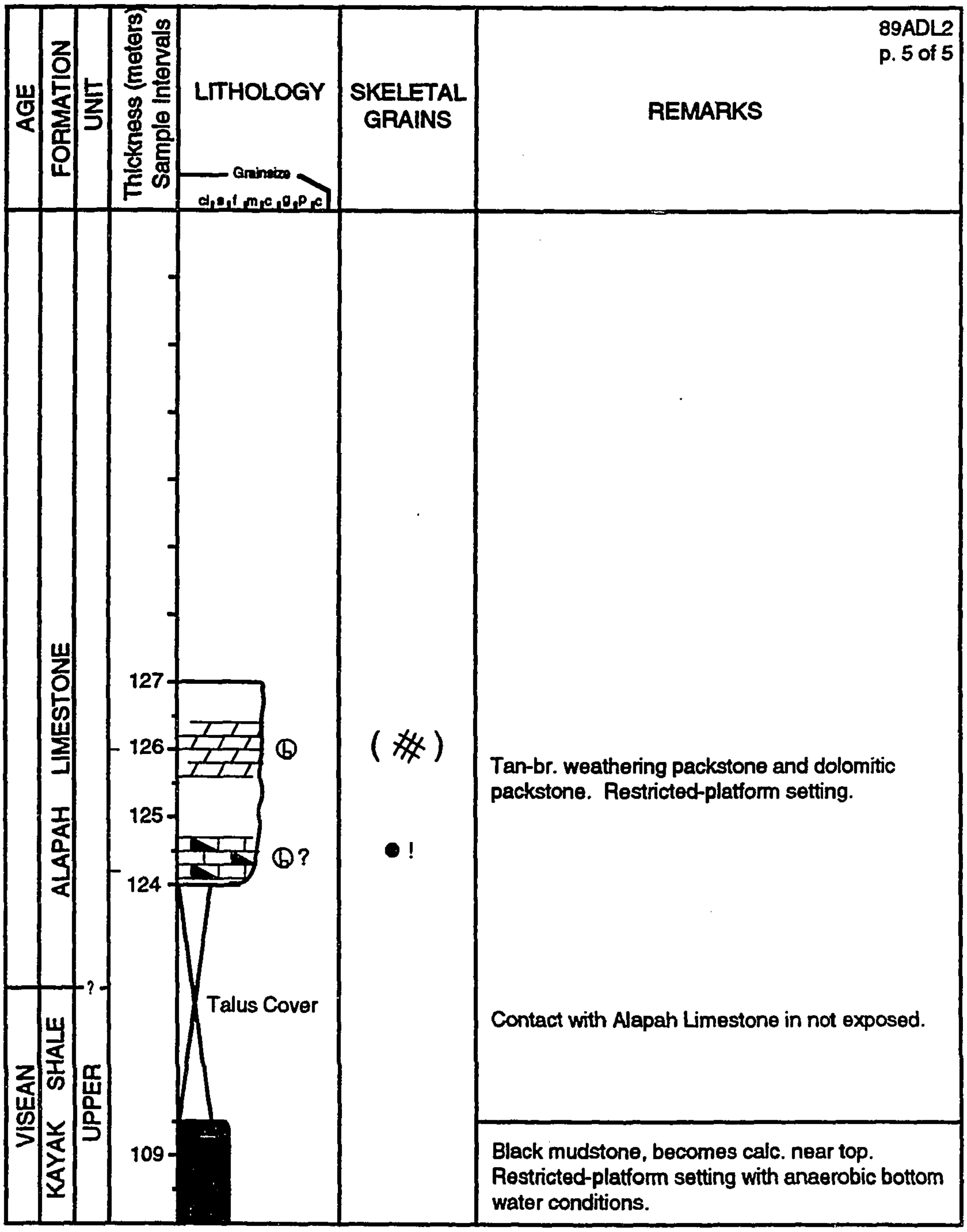
Orange-brown weathering, calc. sandstone; thin, planar beds; basal sand is strongly calc. and characterized by flaggy parting. Abruptly overlain by orange-brown weathering brac., pelecypod, pelmat. packstone with moderate bioturbation, some large vertical, funnel-shaped burrows (1-4 cm wide) infilled with silty lime mudstone, poosible *Monocraterion* burrow. Records deposition in similar setting as 95-96.5 m interval, possibly in shallower water. Influx of terrigenous clastic detritus decreased abruptly above 103.7 m, but was not eliminated.

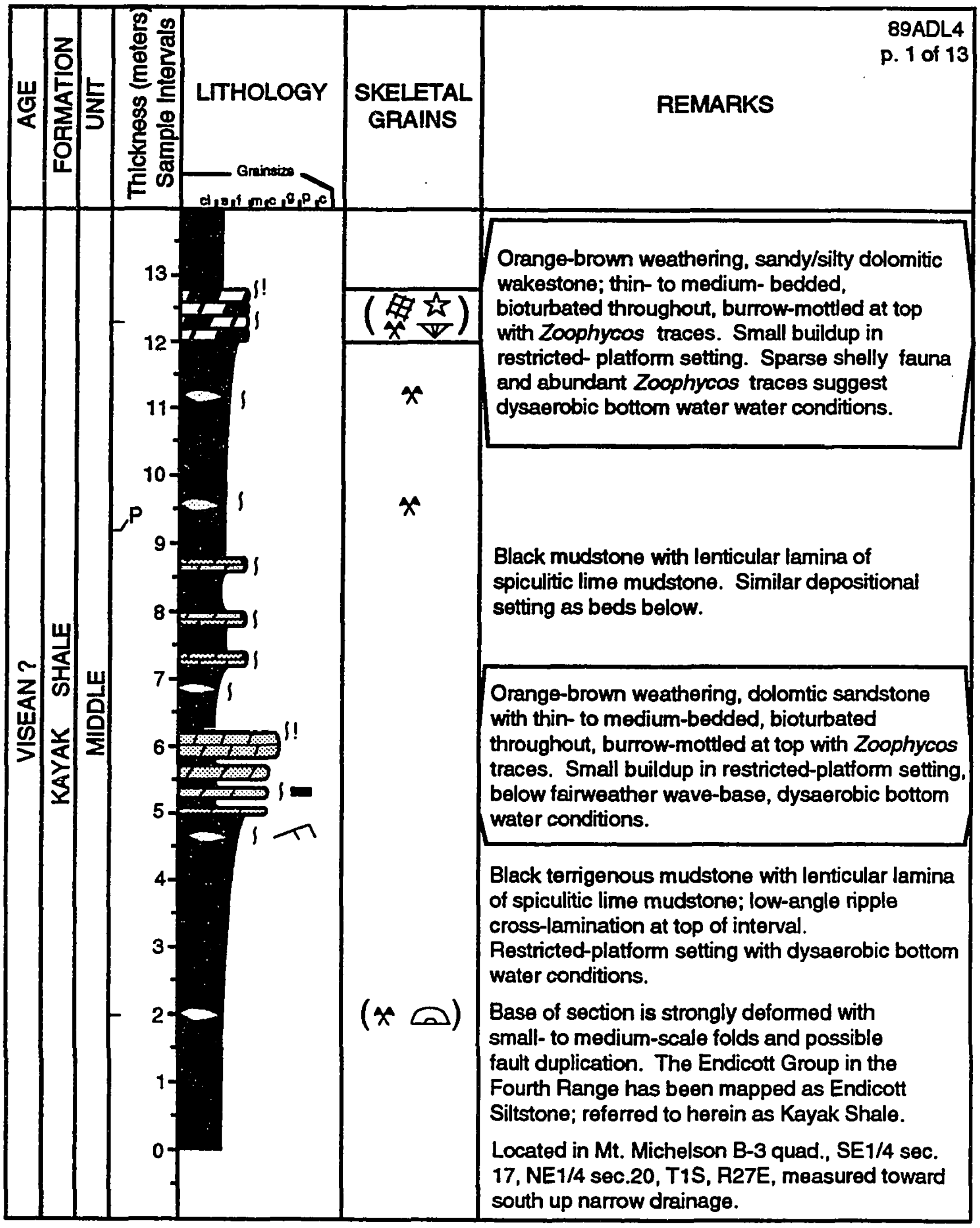
Black, fissile mudstone; passes gradually upsection into mudstone w/ lenticular-laminated, calc. sandstone. Restricted-platform setting with anaerobic bottom water conditions.

Similar depositional setting as suggested for 95-96.5 m interval.

Black, pyritic mudstone with interbedded red-brown weathering silty sandstone; silty sandstone beds are burrow-mottled. Restricted-platform setting. Bottom-water oxygenation fluctuated from anaerobic to dysaerobic.

Orange-brown weathering, calc. silty sandstone or sandy/silty lime mudstone, pyritic, burrow- mottled, abundant traces on bed surfaces. Shoaling-upward cycle in restricted-platform setting with anaerobic to dysaerobic bottom water conditions (as from 80 to 83.5 m).


AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
SKELETAL GRAINS
REMARKS
89ADL2
p. 5 of 5
127
126
125
124
109
ALAPAH LIMESTONE
VISEAN
KAYAK SHALE
UPPER
Talus Cover
(#)
●!
Tan-br. weathering packstone and dolomitic packstone. Restricted-platform setting.
Contact with Alapah Limestone in not exposed.
Black mudstone, becomes calc. near top. Restricted-platform setting with anaerobic bottom water conditions.


89ADL4
p. 1 of 13
AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
cl s vf f m c g p c
SKELETAL GRAINS
REMARKS
VISEAN ?
KAYAK SHALE
MIDDLE
P
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Orange-brown weathering, sandy/silty dolomitic wakestone; thin- to medium- bedded, bioturbated throughout, burrow-mottled at top with Zoophycos traces. Small buildup in restricted- platform setting. Sparse shelly fauna and abundant Zoophycos traces suggest dysaerobic bottom water water conditions.
Black mudstone with lenticular lamina of spiculitic lime mudstone. Similar depositional setting as beds below.
Orange-brown weathering, dolomtic sandstone with thin- to medium-bedded, bioturbated throughout, burrow-mottled at top with Zoophycos traces. Small buildup in restricted-platform setting, below fairweather wave-base, dysaerobic bottom water conditions.
Black terrigenous mudstone with lenticular lamina of spiculitic lime mudstone; low-angle ripple cross-lamination at top of interval. Restricted-platform setting with dysaerobic bottom water conditions.
Base of section is strongly deformed with small- to medium-scale folds and possible fault duplication. The Endicott Group in the Fourth Range has been mapped as Endicott Siltstone; referred to herein as Kayak Shale.
Located in Mt. Michelson B-3 quad., SE1/4 sec. 17, NE1/4 sec.20, T1S, R27E, measured toward south up narrow drainage.

89ADL4
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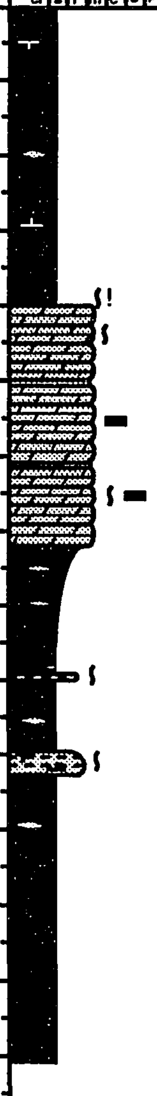
AGE	FORMATION	UNIT	Thickness (meters) Sample Intervals	LITHOLOGY (Grainsize: cl s f m c g p c)	SKELETAL GRAINS	REMARKS
VISEAN ?	KAYAK SHALE	MIDDLE	27, 26, 25, 24			Similar to mudstones lower in section.
			24, 23, 22, 21			Orange-brown dolomitic sandstone, some interbedded sandy macrodolomite; skeletal grains <10%; bioturbated throughout, burrow-mottled at top on interval, abundant *Zoophycos* traces, possible *Nereites*. Restricted-platform setting, below fairweather wave-base, dysaerobic bottom water conditions. Terrigenous probably transported by storm-generated currents.
			20, 19, 18, 17, 16, 15, 14			Black mudstone with thin beds of argillaceous, dolomitic sandstone. Similar depositional setting as mudstone lower in section.

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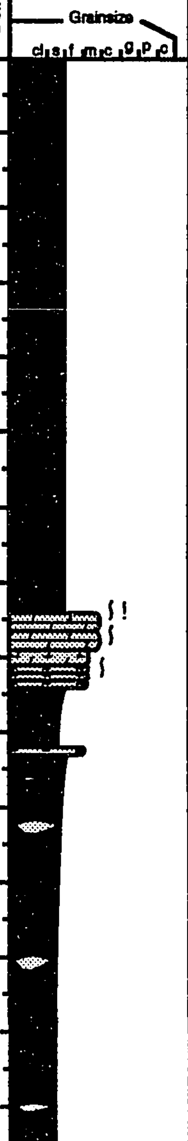
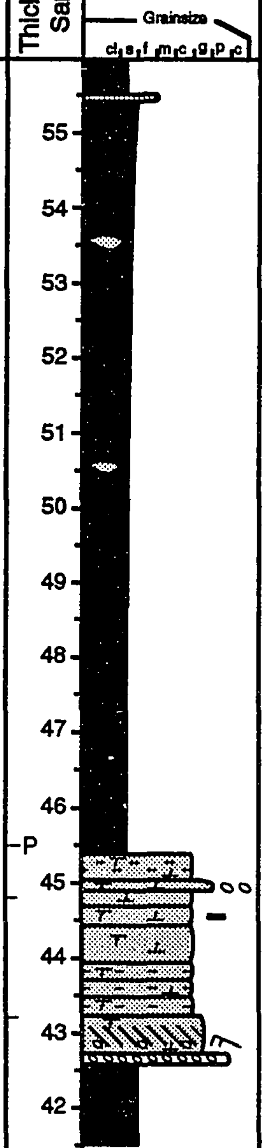
AGE	FORMATION	UNIT	Thickness (meters) Sample Intervals	LITHOLOGY	SKELETAL GRAINS	REMARKS
VISEAN ?	KAYAK SHALE	MIDDLE	28–41			Similar to mudstones lower in section. Black mudstone passes gradually upsection into argillaceous dolomitic sandstone; thin laterally continuous beds; burrow-mottled near top of interval with *Zoophycos* and possible *Nereites*. Restricted-platform setting with dysaerobic bottom water conditions. Thickening- and coarsening-upward trend records progradation of sand sheet into deeper water setting, probably related to storm-generated currents. Black mudstone with lenticular lamina of fine-grained sandstone; sandstone lenses increase in thickness and abundance upsection. Similar depositional setting as mudstones lower in section.

89ADL4
p. 4 of 13

AGE	FORMATION	UNIT	Thickness (meters) Sample Interval	LITHOLOGY	SKELETAL GRAINS	REMARKS
VISEAN	KAYAK SHALE	MIDDLE				



Black shale with lenticular-lamina of fine-grained sanstone. Similar depositional setting as mudstones lower in section.

Interbedded gray- to red-brown weathering coarse-grained sandstone, granule- to pebble-conglomerate, and sandy siltstone; laterally continuous, medium- to thick- bedding; tabular cross- bedding with tangential foresets. Reverse- flow ripple cross-lamination present near base of many foreset beds. Conglomeratic sandstone near top of interval contains crudely developed, thick horizontal laminae. Ammonite fossil collected from basal conglomerate (Gruzlovic, personal comm., 1990). Basal scour, pebble conglomerate, and traction-generated structures suggest deposition from high-energy currents. Probably deposited in a tidal channel scoured into mundstone in shallow (?) restricted-platform setting with anaerobic bottom water conditions. Unidirectional current indicators suggest an asymmetric time-velocity profile for tidal currents. Alternatively, could record deposition as tidal sand ridge in offshore setting.

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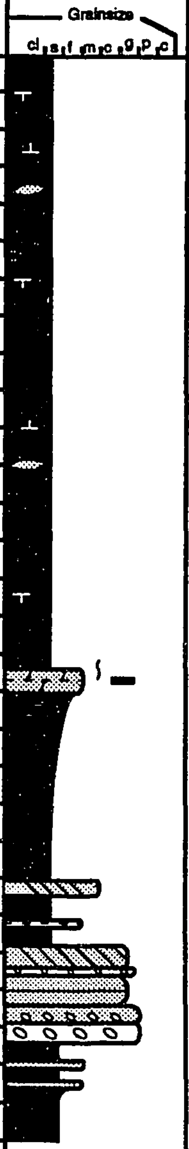
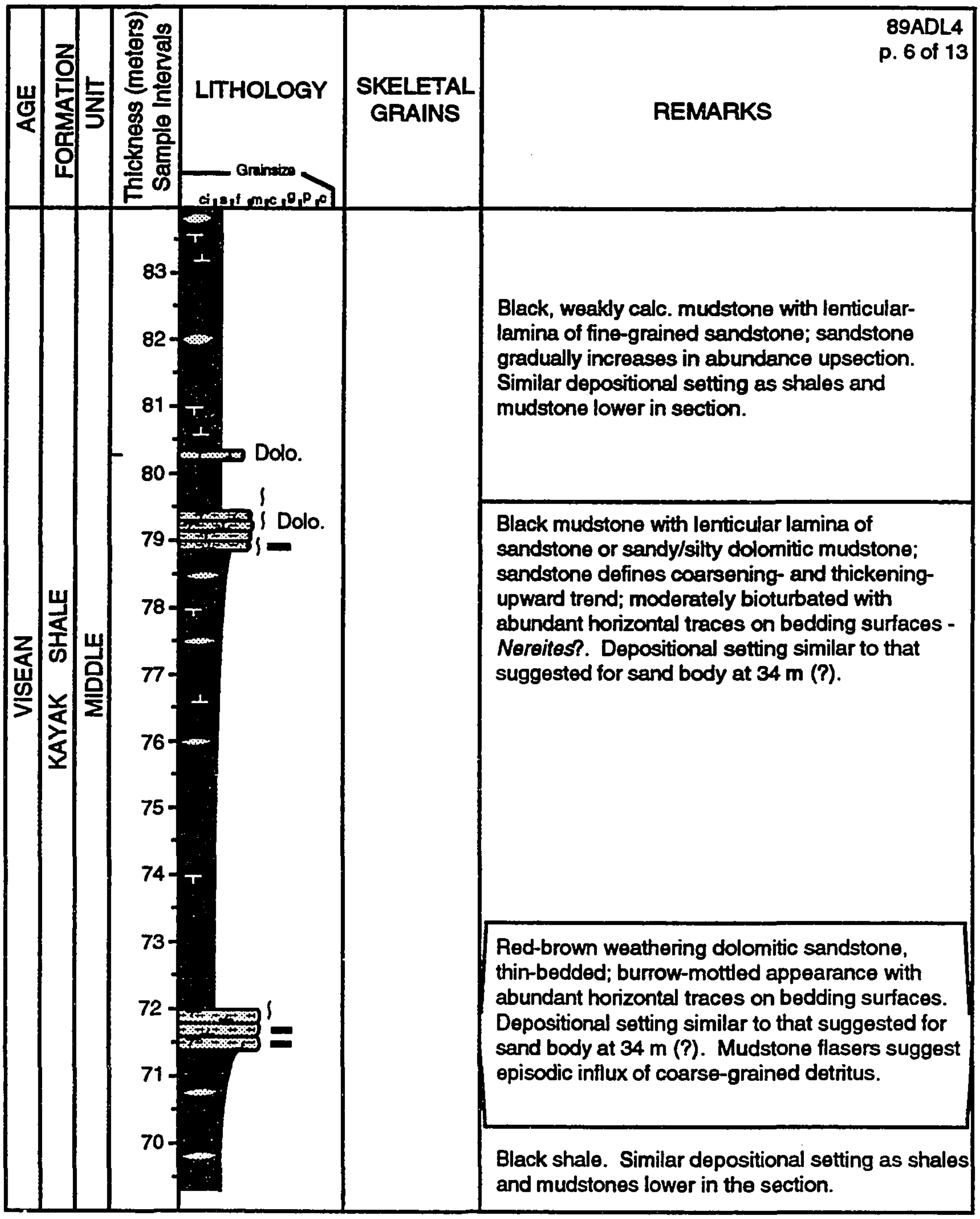
p. 5 of 13

AGE	FORMATION	UNIT	Thickness (meters) Sample Intervals	LITHOLOGY	SKELETAL GRAINS	REMARKS
VISEAN	KAYAK SHALE	MIDDLE	69, 68, 67, 66, 65, 64, 63, 62, 61, 60, 59, 58, 57, P, 56			Black mudstone, weakly calc.; abundant lenticular- lamina of orange-brown weathering dolomtic sandstone. Similar depositional setting as mudstones lower in section.
						Black mudstone with lenticular lamina of orange-brown weathering sandstone; sandstones gradually thicken upsection, capped with argillaceous dolomitic sandstone; uppermost sandstone bed is burrow-mottled with possible *Nereites* visible on bed surface. Restricted-platform setting with dysaerobic bottom water conditions. Sand transport probably from storm-generated currents.
						Interbedded orange-brown weathering sandstone and granule conglomerate; minor mudstone flasers. Deposited in setting similar to that interpreted for sand body from 42.6-45.4 m; mudstone flasers indicate fluctuating energy conditions. This is consistent with deposition in a tide influenced setting.


89ADL4
p. 6 of 13
AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
SKELETAL GRAINS
REMARKS
VISEAN
KAYAK SHALE
MIDDLE
83
82
81
80
79
78
77
76
75
74
73
72
71
70
Dolo.
Dolo.
Black, weakly calc. mudstone with lenticular-lamina of fine-grained sandstone; sandstone gradually increases in abundance upsection. Similar depositional setting as shales and mudstone lower in section.
Black mudstone with lenticular lamina of sandstone or sandy/silty dolomitic mudstone; sandstone defines coarsening- and thickening-upward trend; moderately bioturbated with abundant horizontal traces on bedding surfaces - *Nereites*?. Depositional setting similar to that suggested for sand body at 34 m (?).
Red-brown weathering dolomitic sandstone, thin-bedded; burrow-mottled appearance with abundant horizontal traces on bedding surfaces. Depositional setting similar to that suggested for sand body at 34 m (?). Mudstone flasers suggest episodic influx of coarse-grained detritus.
Black shale. Similar depositional setting as shales and mudstones lower in the section.

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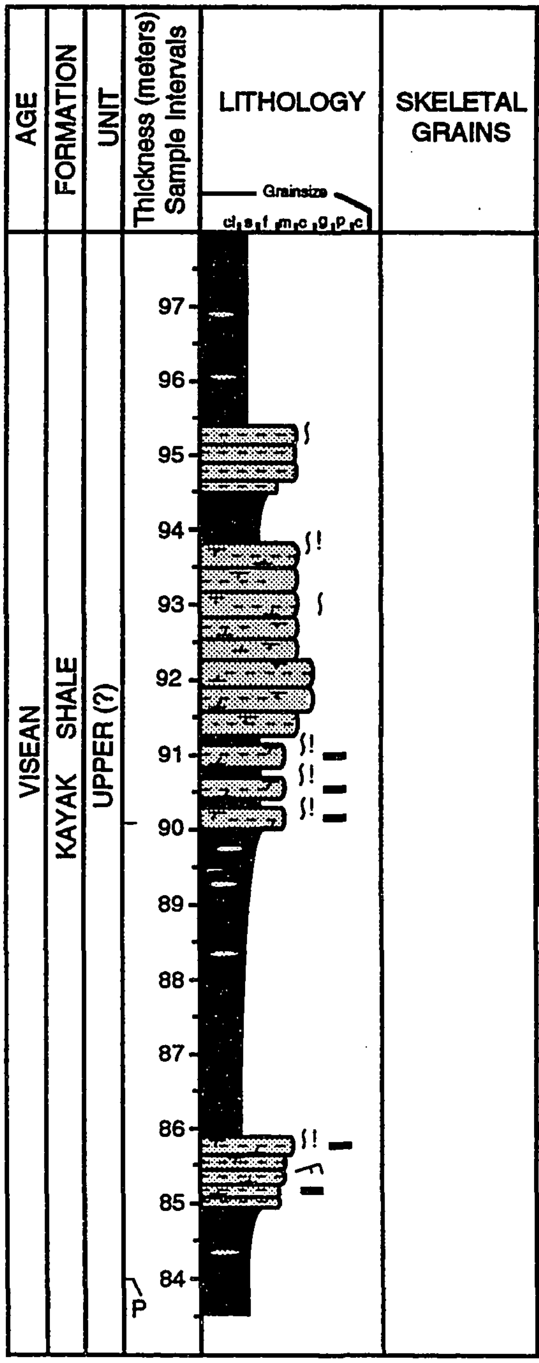


REMARKS

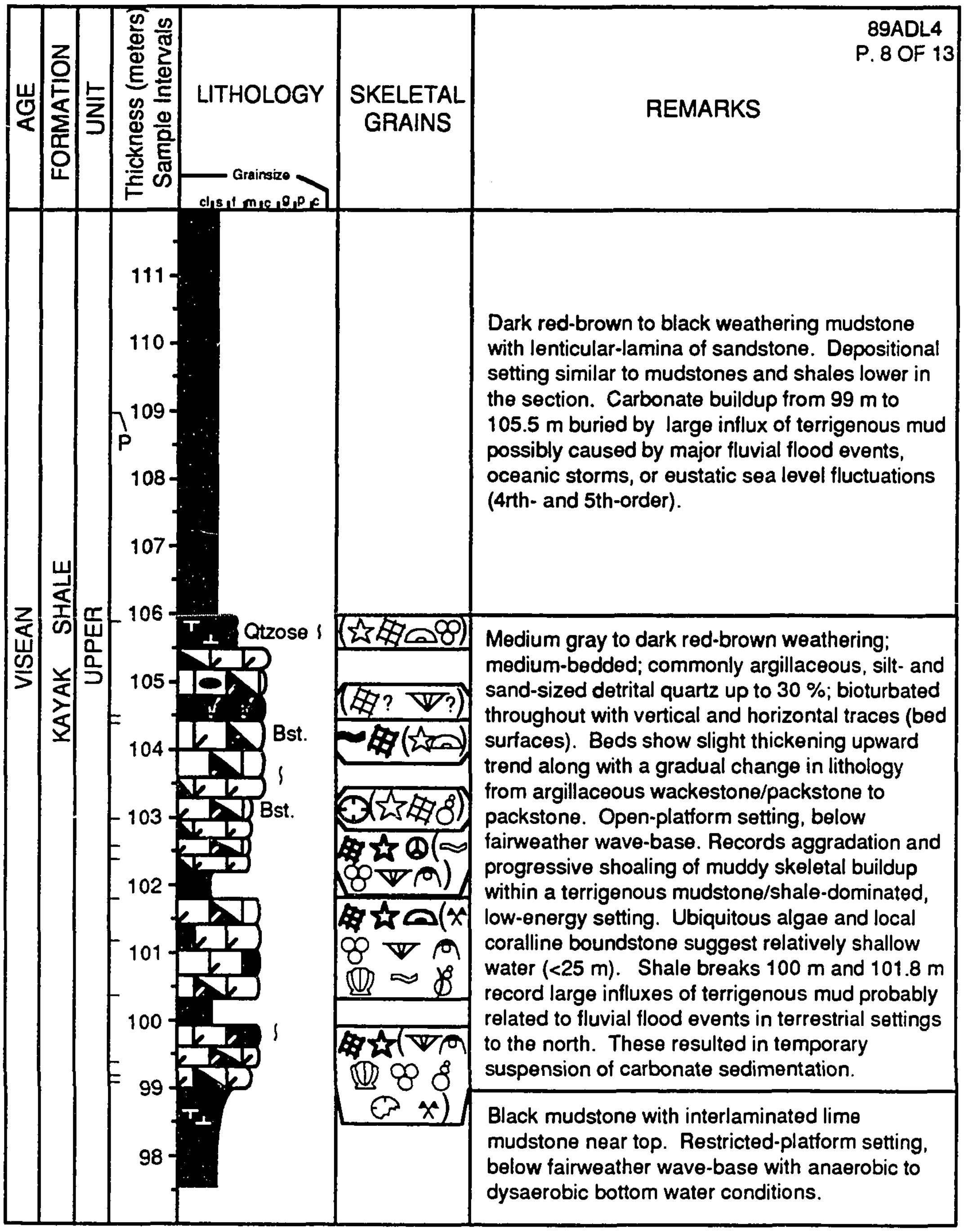
Similar to mudstones and shales lower in section.

Orange-brown to red-brown weathering argillaceous dolomitic sandstone; thin- to medium-bedded, some thin interbeds of mudstone; burrow-mottled near top of interval, common *Zoophycos* and possible *Nereites*? Restricted-platform setting, probably below fairweather wave-base with dysaerobic bottom water conditions. Sand probably transported by storm-generated currents. Prograding and aggrading sand sheet (?) resulted in sediment surface rising above anaerobic bottom water layer so annelid worms could colonize the substrate. Mudstone drapes indicate fluctuating energy levels. Depositional setting similar to sand body at 34 m (?).

Black shale with lenticular-lamina of sandstone. Depositional setting similar to mudstones and shales lower in section.

Red-brown weathering dolomitic sandstone; laterally continuous beds, flaggy parting; burrow-mottled horizontal and vertical burrows common. Depositional setting similar to sand body at 34 m(?).

Black mudstone. Depositional setting similar to mudstones and shales lower in section.


89ADL4
P. 8 OF 13
AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
SKELETAL GRAINS
REMARKS
VISEAN
KAYAK SHALE
UPPER
111
110
109
P
108
107
106
105
104
103
102
101
100
99
98
Qtzose
Bst.
Bst.
Dark red-brown to black weathering mudstone with lenticular-lamina of sandstone. Depositional setting similar to mudstones and shales lower in the section. Carbonate buildup from 99 m to 105.5 m buried by large influx of terrigenous mud possibly caused by major fluvial flood events, oceanic storms, or eustatic sea level fluctuations (4rth- and 5th-order).
Medium gray to dark red-brown weathering; medium-bedded; commonly argillaceous, silt- and sand-sized detrital quartz up to 30 %; bioturbated throughout with vertical and horizontal traces (bed surfaces). Beds show slight thickening upward trend along with a gradual change in lithology from argillaceous wackestone/packstone to packstone. Open-platform setting, below fairweather wave-base. Records aggradation and progressive shoaling of muddy skeletal buildup within a terrigenous mudstone/shale-dominated, low-energy setting. Ubiquitous algae and local coralline boundstone suggest relatively shallow water (<25 m). Shale breaks 100 m and 101.8 m record large influxes of terrigenous mud probably related to fluvial flood events in terrestrial settings to the north. These resulted in temporary suspension of carbonate sedimentation.
Black mudstone with interlaminated lime mudstone near top. Restricted-platform setting, below fairweather wave-base with anaerobic to dysaerobic bottom water conditions.

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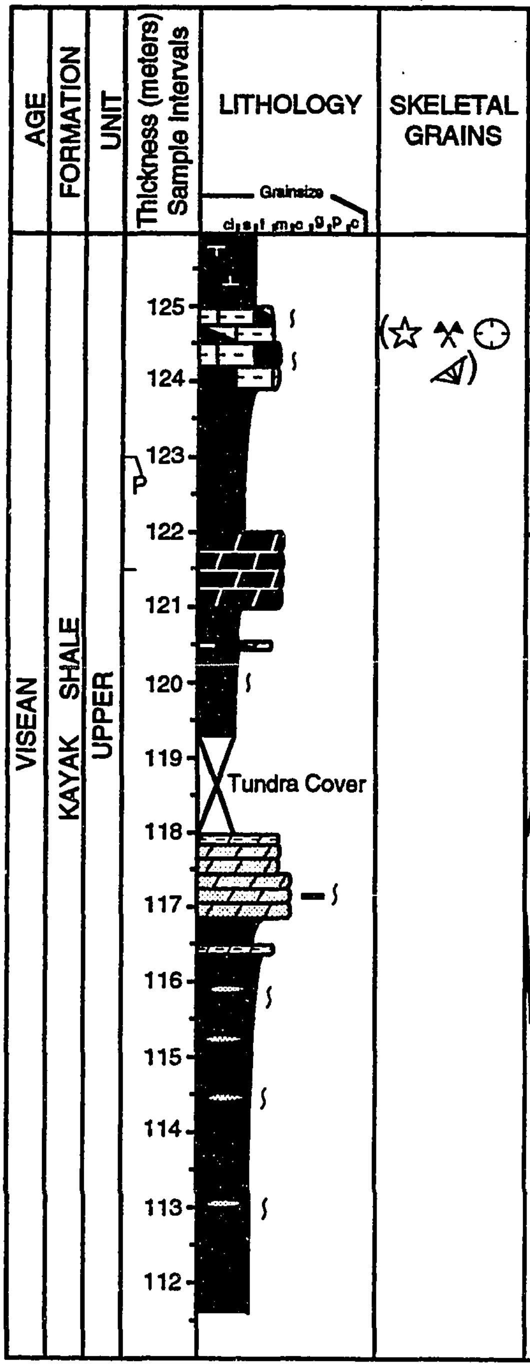


REMARKS

Black mudstone/shale with lenticular-lamina of pelmatozoan-bryozoan wackestone/packstone.

Burrow-mottled. Depositional setting similar to 99 to 106 m interval.

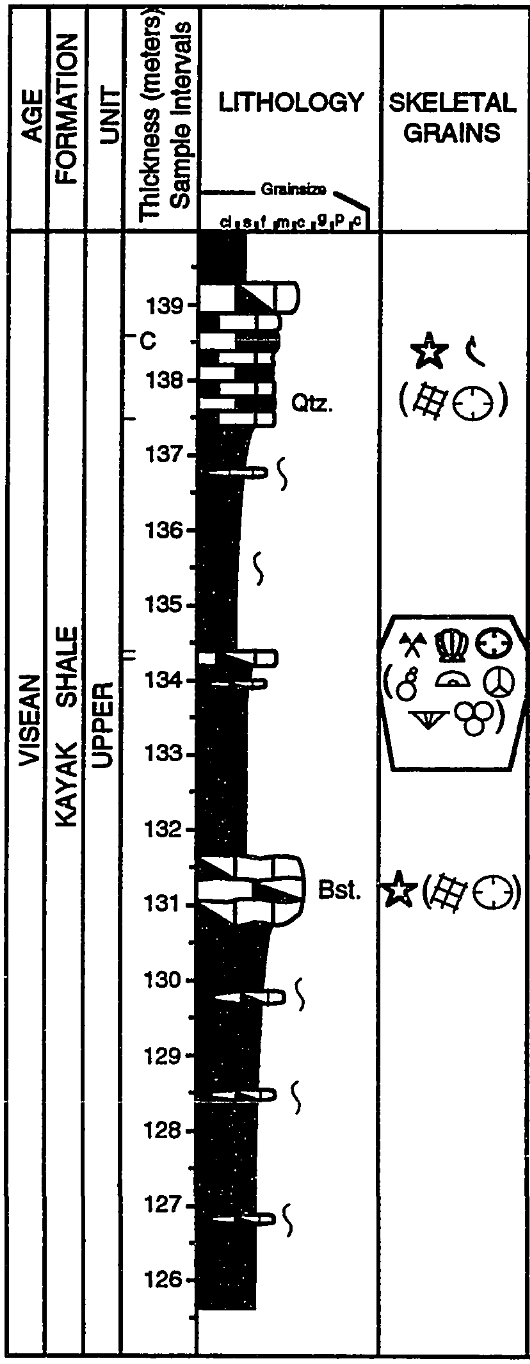
Black mudstone/shale with lenticular-lamina of pelmatozoan-bryozoan wackestone/packstone.

Black mudstone/shale with lenticular laminated wackestone/packstone, passes upsection into orange-brown weathering, medium-bedded, sandy/spiculitic (?) dolomitic mudstone. Restricted to marginally restricted-platform setting as minor shoaling-upward succession. Records small muddy carbonate buildup that developed in a terrigenous mud-dominated setting, below fairweather wave-base.

Orange-brown weathering dolomitic sandstone or sandy dolomite(?); thin- to medium-bedded, flaggy parting; bioturbation increases upward, horizontal traces on bed surfaces at top of succession, possible *Nerietes* (?). Depositional setting similar to dolomitic sandstones lower in section.

Black shale with red-brown and orange-brown weathering lenticular-lamina of sandstone; sandstone lamina are moderately bioturbated. Depositional setting similar to mudstones and shales lower in section, only bioturbation indicates dysaerobic bottom water conditions, at least locally.

89ADL4
p. 10 of 13



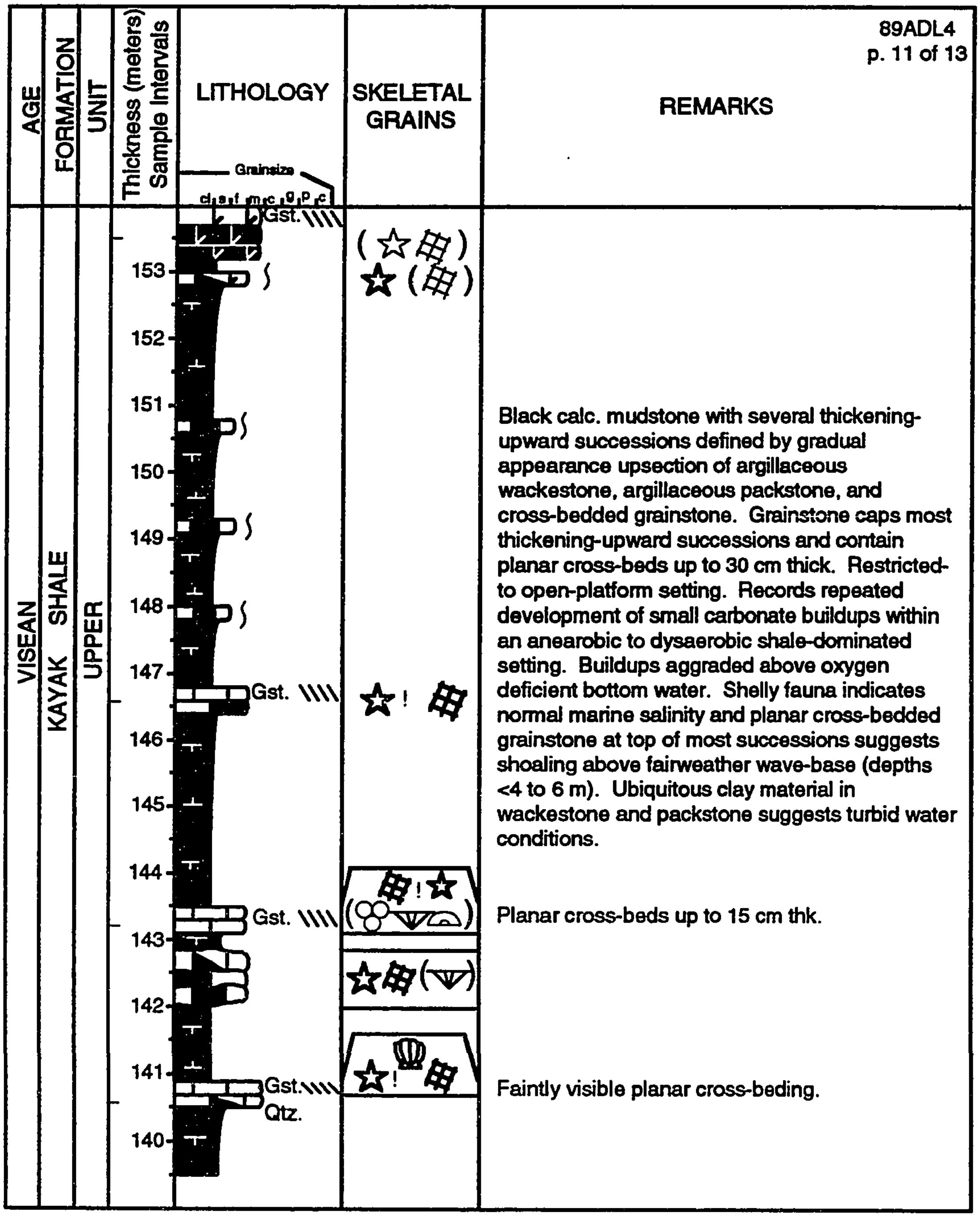
REMARKS

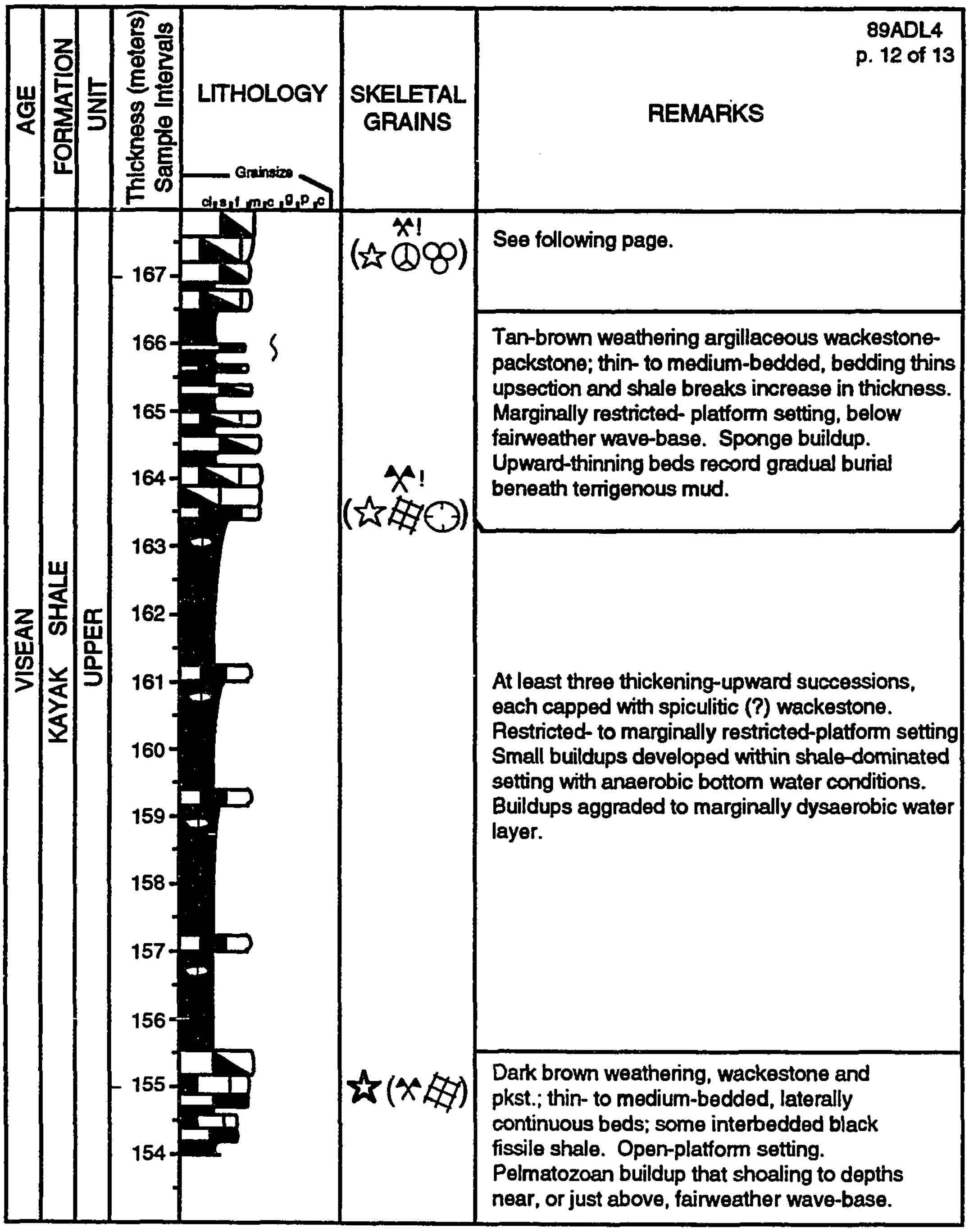
Package thickens toward top; upper bed is argillaceous packstone with patches of coralline boundstone; *Syringipora* identified in thin section, *Lithostrotionella* seen in outcrop; silt- and sand-sized detrital quartz up to 20%; Icthyliths fish teeth and dermal plates in conodont sample (Harris, 1991). Depositional setting is similar to coralline boundstone lower in section.

Black mudstone/shale with lenticular-lamina of bioturbated wackestone/packstone. Depositional setting similar to mudstones/shales with lenticular lamina of limestone lower in section.

Black mudstone/shale. Succession capped by argillaceous spiculitic packstone bed; packstone bed thins along local strike - lenticular geometry? Marginally restricted-platform setting, below fairweather wave-base. Small sponge buildup.

Black mudstone with lenticular-lamina of bioturbated argillaceous wackestone/packstone; wackestone/packstone lamina thicken upsection to thin to medium beds; interval is capped by argillaceous packstone/coralline boundstone bed with *Lithostrotionella* in growth position. Marginally restricted- to open-platform setting, below fairweather wave-base. Records small carbonate buildup, possibly a patch reef, that developed within a terrigenous mud/shale-dominated setting that had anaerobic to dysaerobic bottom water conditions. Patch reef aggraded above oxygen depleted bottom water layer into a marginally dysaerobic to aerobic water layer.


89ADL4
p. 11 of 13
AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
VISEAN
KAYAK SHALE
UPPER
153
152
151
150
149
148
147
146
145
144
143
142
141
140
Gst.
Gst.
Gst.
Gst.
Qtz.
Black calc. mudstone with several thickening-upward successions defined by gradual appearance upsection of argillaceous wackestone, argillaceous packstone, and cross-bedded grainstone. Grainstone caps most thickening-upward successions and contain planar cross-beds up to 30 cm thick. Restricted-to open-platform setting. Records repeated development of small carbonate buildups within an anearobic to dysaerobic shale-dominated setting. Buildups aggraded above oxygen deficient bottom water. Shelly fauna indicates normal marine salinity and planar cross-bedded grainstone at top of most successions suggests shoaling above fairweather wave-base (depths <4 to 6 m). Ubiquitous clay material in wackestone and packstone suggests turbid water conditions.
Planar cross-beds up to 15 cm thk.
Faintly visible planar cross-beding.



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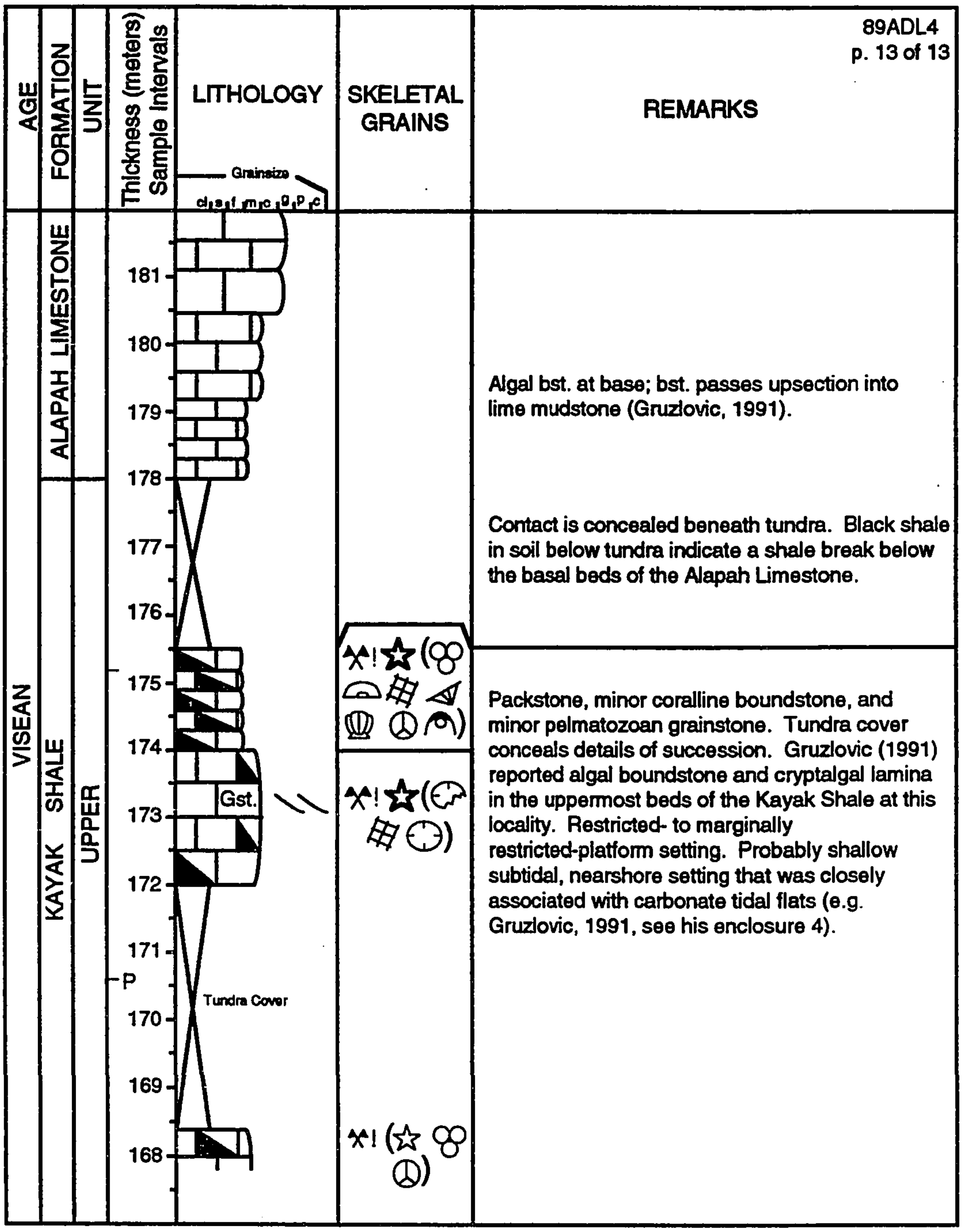
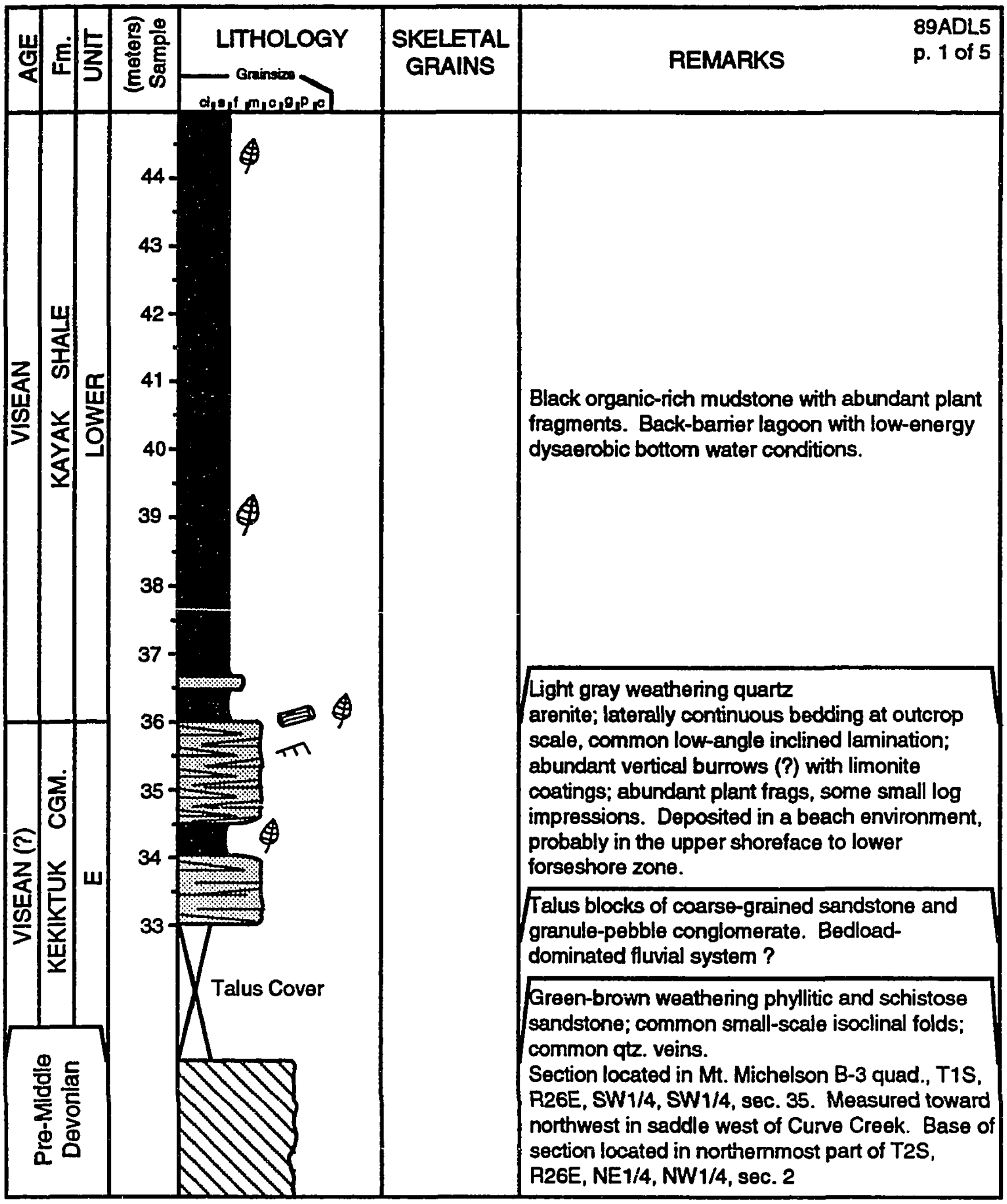
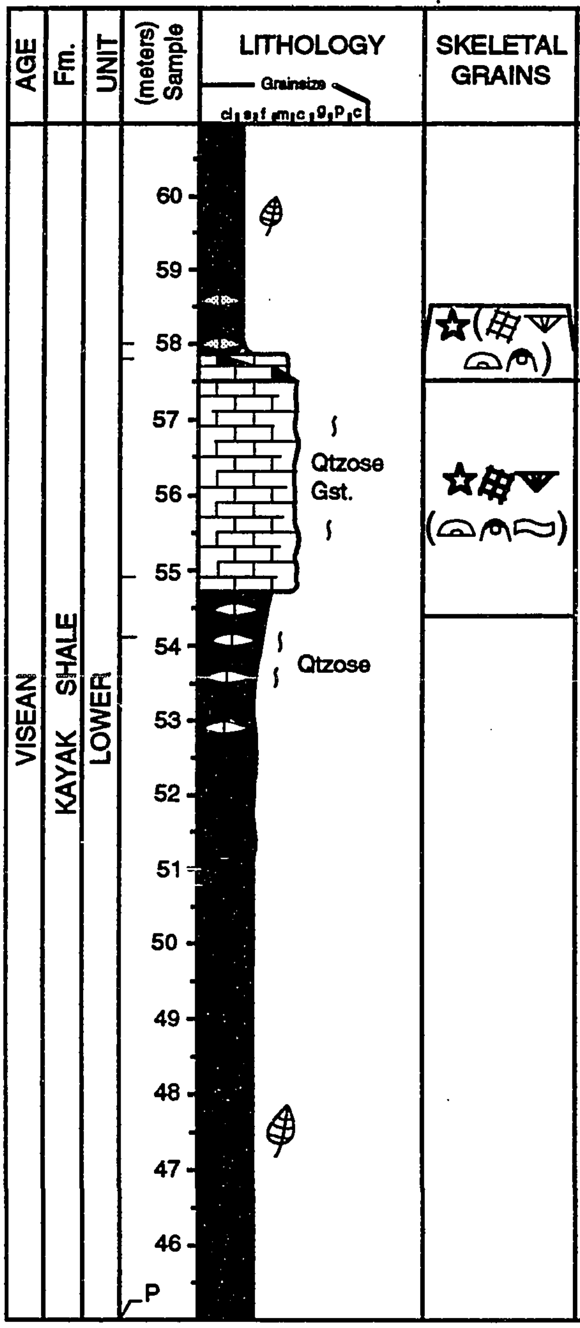
p. 12 of 13
AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
SKELETAL GRAINS
REMARKS
VISEAN
KAYAK SHALE
UPPER
167
166
165
164
163
162
161
160
159
158
157
156
155
154
See following page.
Tan-brown weathering argillaceous wackestone-packstone; thin- to medium-bedded, bedding thins upsection and shale breaks increase in thickness. Marginally restricted- platform setting, below fairweather wave-base. Sponge buildup. Upward-thinning beds record gradual burial beneath terrigenous mud.
At least three thickening-upward successions, each capped with spiculitic (?) wackestone. Restricted- to marginally restricted-platform setting Small buildups developed within shale-dominated setting with anaerobic bottom water conditions. Buildups aggraded to marginally dysaerobic water layer.
Dark brown weathering, wackestone and pkst.; thin- to medium-bedded, laterally continuous beds; some interbedded black fissile shale. Open-platform setting. Pelmatozoan buildup that shoaling to depths near, or just above, fairweather wave-base.


89ADL4
p. 13 of 13
AGE
FORMATION
UNIT
Thickness (meters)
Sample Intervals
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
VISEAN
ALAPAH LIMESTONE
KAYAK SHALE
UPPER
181
180
179
178
177
176
175
174
173
172
171
P
170
169
168
Gst.
Tundra Cover
Algal bst. at base; bst. passes upsection into lime mudstone (Gruzlovic, 1991).
Contact is concealed beneath tundra. Black shale in soil below tundra indicate a shale break below the basal beds of the Alapah Limestone.
Packstone, minor coralline boundstone, and minor pelmatozoan grainstone. Tundra cover conceals details of succession. Gruzlovic (1991) reported algal boundstone and cryptalgal lamina in the uppermost beds of the Kayak Shale at this locality. Restricted- to marginally restricted-platform setting. Probably shallow subtidal, nearshore setting that was closely associated with carbonate tidal flats (e.g. Gruzlovic, 1991, see his enclosure 4).


AGE
Fm.
UNIT
(meters) Sample
LITHOLOGY
Grainsize
c s f m c g p c
SKELETAL GRAINS
REMARKS
89ADL5
p. 1 of 5
VISEAN
KAYAK SHALE
LOWER
VISEAN (?)
KEKIKTUK CGM.
E
Pre-Middle Devonian
44
43
42
41
40
39
38
37
36
35
34
33
Talus Cover
Black organic-rich mudstone with abundant plant fragments. Back-barrier lagoon with low-energy dysaerobic bottom water conditions.
Light gray weathering quartz arenite; laterally continuous bedding at outcrop scale, common low-angle inclined lamination; abundant vertical burrows (?) with limonite coatings; abundant plant frags, some small log impressions. Deposited in a beach environment, probably in the upper shoreface to lower forseshore zone.
Talus blocks of coarse-grained sandstone and granule-pebble conglomerate. Bedload-dominated fluvial system ?
Green-brown weathering phyllitic and schistose sandstone; common small-scale isoclinal folds; common qtz. veins.
Section located in Mt. Michelson B-3 quad., T1S, R26E, SW1/4, SW1/4, sec. 35. Measured toward northwest in saddle west of Curve Creek. Base of section located in northernmost part of T2S, R26E, NE1/4, NW1/4, sec. 2

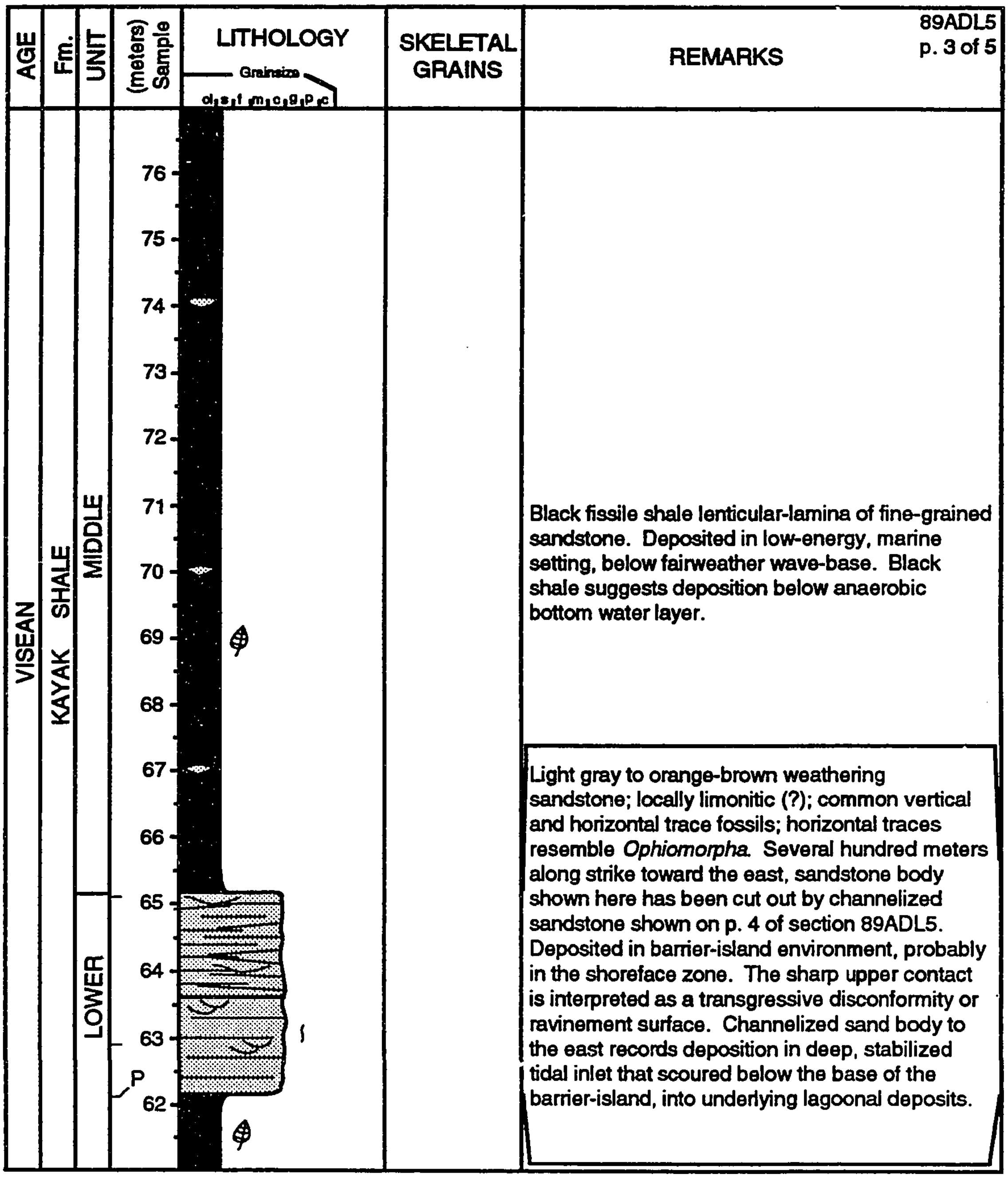
89ADL5
p. 2 of 5

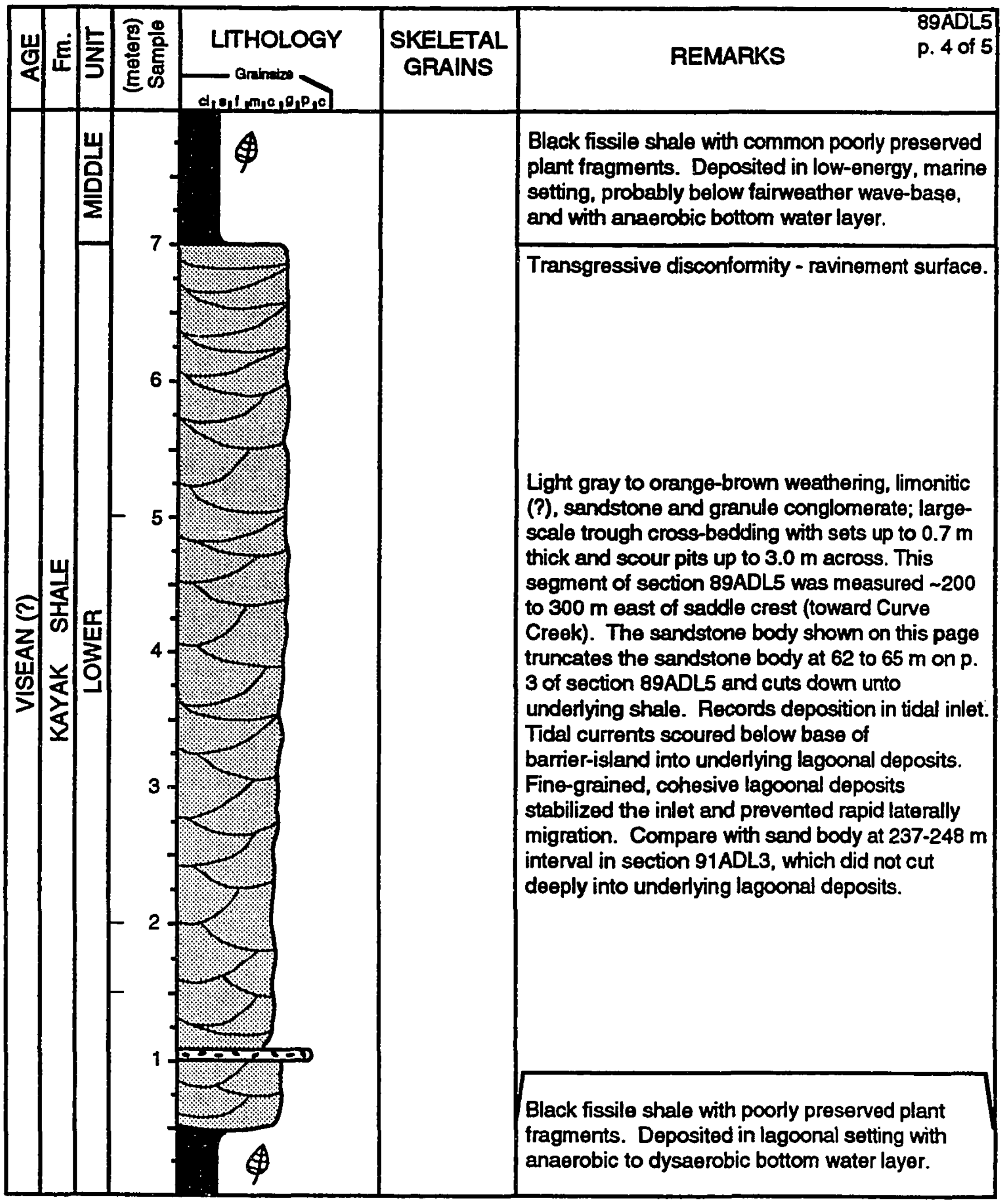


REMARKS

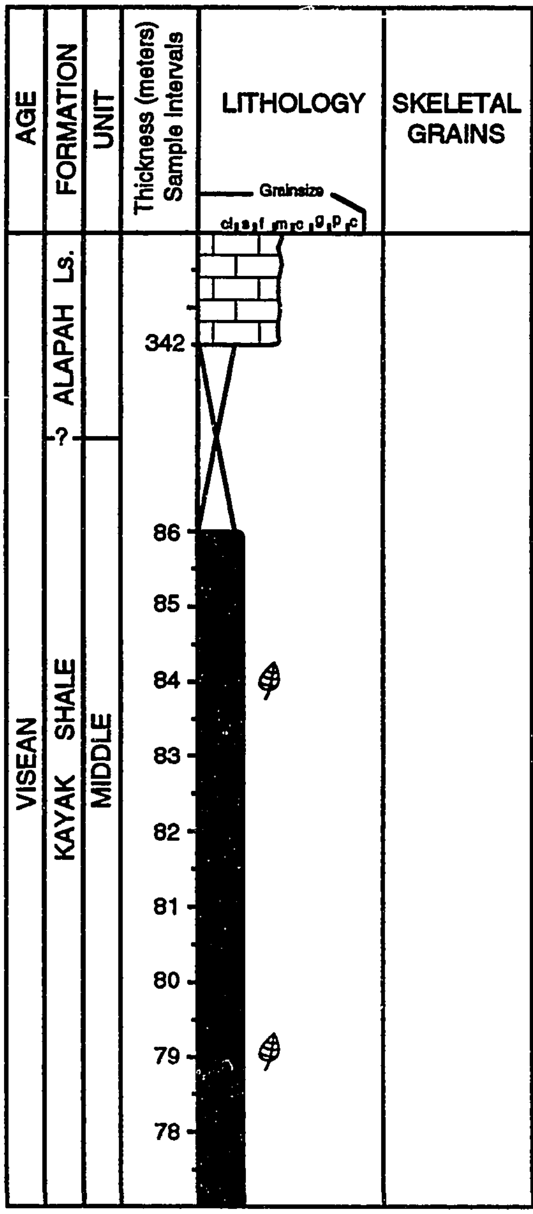
Black fissile mudstone with common plant fragments. Back-barrier lagoon setting, low-energy, anaerobic to dysaerobic bottom water conditions.

Black organic-rich, fissile mudstone/shale with lenticular-lamina of fine-grained sandstone/sandy limestone; lamina thicken gradually upsection; scolecodonts recovered from palynological sample (Utting, 1990). Upward-thickening trend capped by light orange-brown weathering packstone/grainstone; thin-bedded, flaggy parting; skeletal grains are highly abraded and oriented parallel to bedding; common sand-sized quartz scattered throughout; bed surfaces in many places coated with black film - dead oil? Deposited in a back-barrier lagoon setting. Black organic-rich mudstone suggests oxygen deficient bottom water layer. Scolecodonts indicate saline conditions (brackish or normal marine ?) and dysaerobic oxygen levels locally. The broken and abraded condition of skeletal grains and ubiquitous presence of sand-sized quartz grains suggest hydraulic transport in energetic conditions. The shelly fauna was derived from an open-marine setting seaward (south) of the barrier-island/lagoon. This suggests that sandy grainstone records storm-generated washover deposits. Skeletal material was transported landward (north) by storm surges and washed over a quartz sand barrier-island. As storm surges overtopped barrier-islands they entrained sand-sized qtz. grains.


AGE
Fm.
UNIT
(meters) Sample
LITHOLOGY
Grainsize
SKELETAL GRAINS
REMARKS
89ADL5
p. 3 of 5
VISEAN
KAYAK SHALE
MIDDLE
LOWER
76
75
74
73
72
71
70
69
68
67
66
65
64
63
62
P
Black fissile shale lenticular-lamina of fine-grained sandstone. Deposited in low-energy, marine setting, below fairweather wave-base. Black shale suggests deposition below anaerobic bottom water layer.
Light gray to orange-brown weathering sandstone; locally limonitic (?); common vertical and horizontal trace fossils; horizontal traces resemble *Ophiomorpha*. Several hundred meters along strike toward the east, sandstone body shown here has been cut out by channelized sandstone shown on p. 4 of section 89ADL5. Deposited in barrier-island environment, probably in the shoreface zone. The sharp upper contact is interpreted as a transgressive disconformity or ravinement surface. Channelized sand body to the east records deposition in deep, stabilized tidal inlet that scoured below the base of the barrier-island, into underlying lagoonal deposits.


AGE
Fm.
UNIT
(meters) Sample
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
89ADL5
p. 4 of 5
VISEAN (?)
KAYAK SHALE
MIDDLE
LOWER
7
6
5
4
3
2
1
Black fissile shale with common poorly preserved plant fragments. Deposited in low-energy, marine setting, probably below fairweather wave-base, and with anaerobic bottom water layer.
Transgressive disconformity - ravinement surface.
Light gray to orange-brown weathering, limonitic (?), sandstone and granule conglomerate; large-scale trough cross-bedding with sets up to 0.7 m thick and scour pits up to 3.0 m across. This segment of section 89ADL5 was measured ~200 to 300 m east of saddle crest (toward Curve Creek). The sandstone body shown on this page truncates the sandstone body at 62 to 65 m on p. 3 of section 89ADL5 and cuts down unto underlying shale. Records deposition in tidal inlet. Tidal currents scoured below base of barrier-island into underlying lagoonal deposits. Fine-grained, cohesive lagoonal deposits stabilized the inlet and prevented rapid laterally migration. Compare with sand body at 237-248 m interval in section 91ADL3, which did not cut deeply into underlying lagoonal deposits.
Black fissile shale with poorly preserved plant fragments. Deposited in lagoonal setting with anaerobic to dysaerobic bottom water layer.

89ADL5
p. 5 of 5

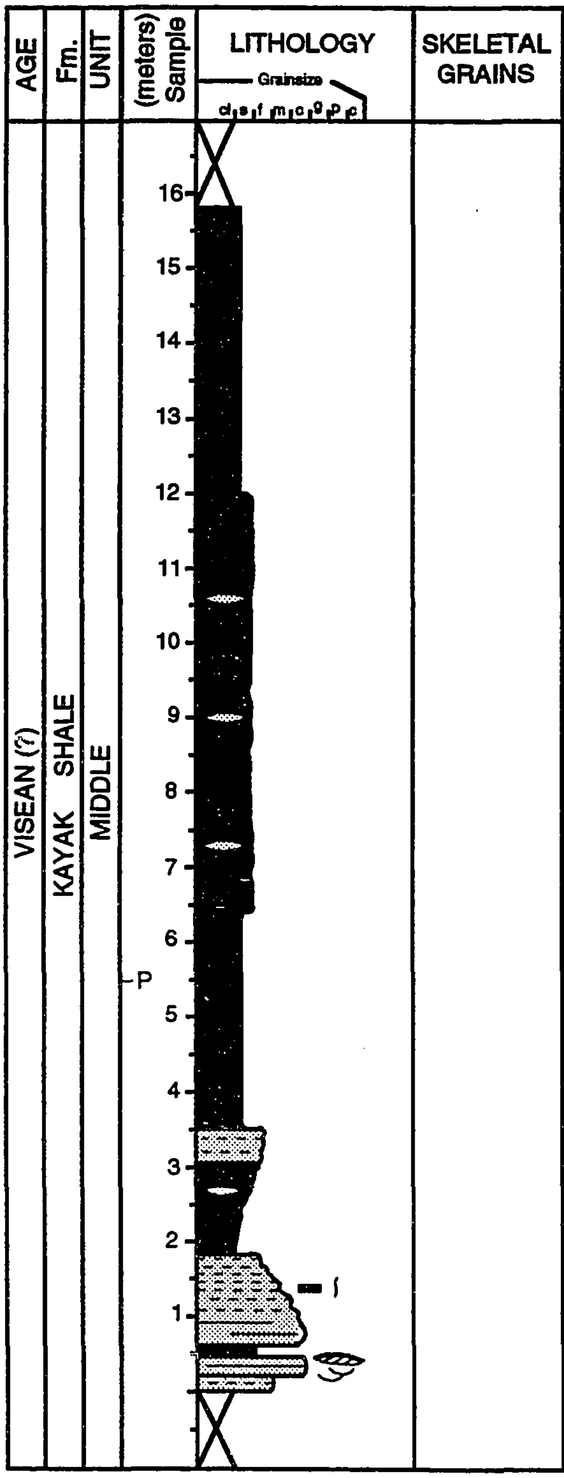


REMARKS

Contact between Kayak and Alapah is not exposed; rubble covered, south-facing slope on north side of saddle. Basal exposed Alapah is light gray lime mudstone.

Exposures poor to absent. Base of north dipping slope on south side of saddle, immediately west of Curve Creek.

Black fissile shale. Deposited in low-energy marine setting, below fairweather wave-base, with anaerobic to dysaerobic bottom water conditions.



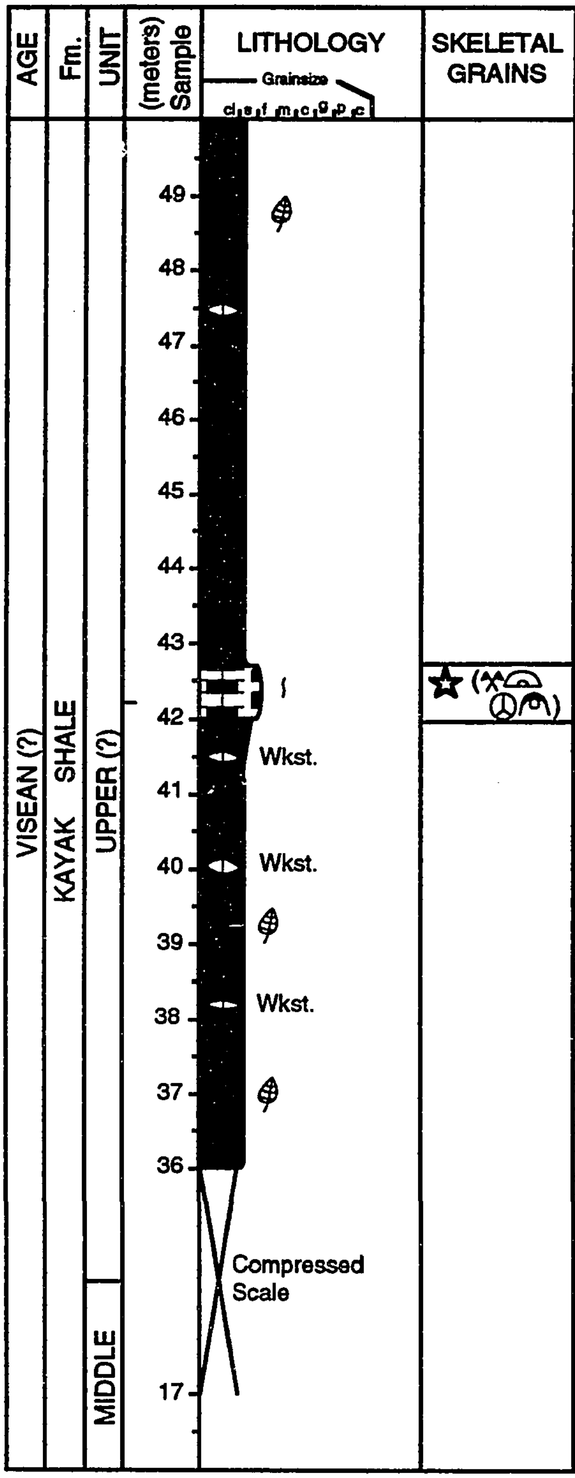
REMARKS 89ADL8 p. 1 of 11

Black shale with well-developed slaty cleavage. Low-energy marine setting with anaerobic bottom water conditions, below fairweather wave-base.

Black fissile shale, passes abruptly at 6.5 m into orange-brown weathering mudstone with lenticular lamina of fine-grained sandstone; common small-scale folds. Low-energy marine setting with anaerobic bottom water layer. Lenticular-lamina of sandstone indicate fluctuating energy conditions and/or supply of coarse-grained detritus. Distance from strand line ?

Interbedded gray to tan-brown weathering sandstone, mudstone, and black shale; trough cross-bedding and possible hummocky cross-bedding near base. Deposited in marine setting at least at depths near fairweather wave-base, and probably at depths between fairweather and storm wave-base. Mudstone flasers indicate fluctuating energy conditions, probably due to a tidal influence.

Base of Endicott Group is not exposed; exposures of pre-Middle Devonian quartz-semischist and phyllite are present on south side of Franklin Creek, north of the base of section 89ADL8. Section located in Mt. Michelson A-3 quad., T3S, R28E, NE1/4, NW1/4 sec. 29, mesured toward south, up narrow drainage. Much detachment folding evident in overlying Lisburne Group.



REMARKS

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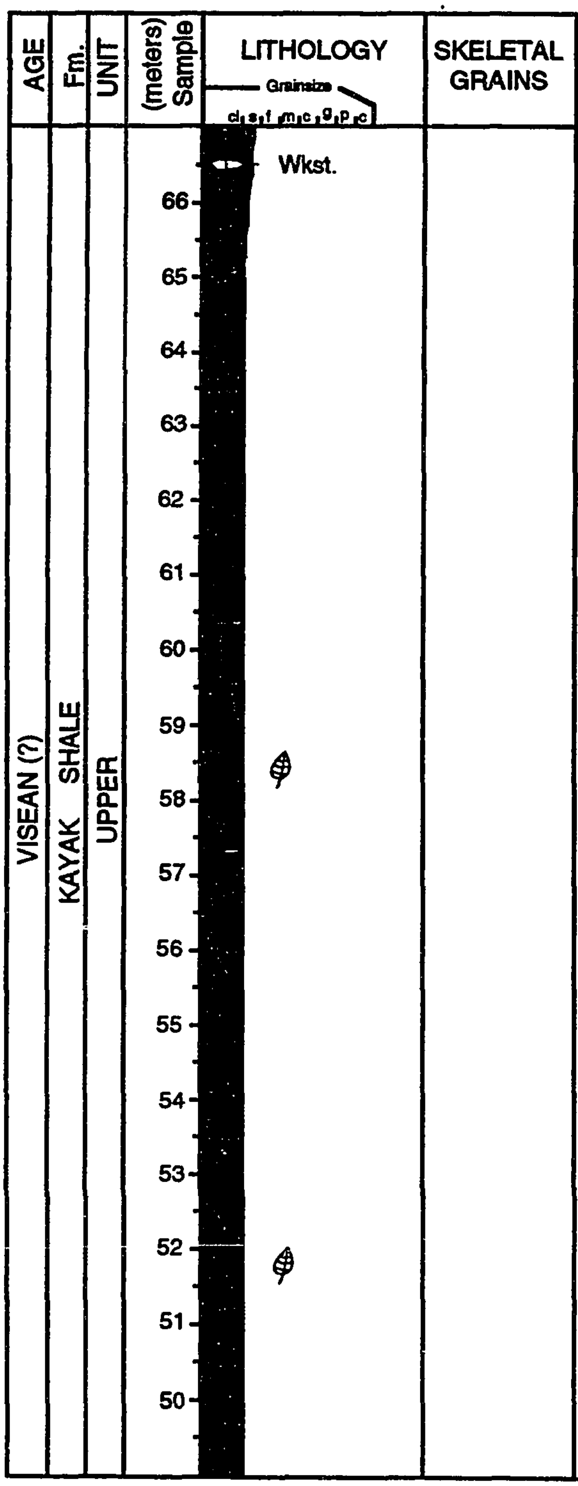
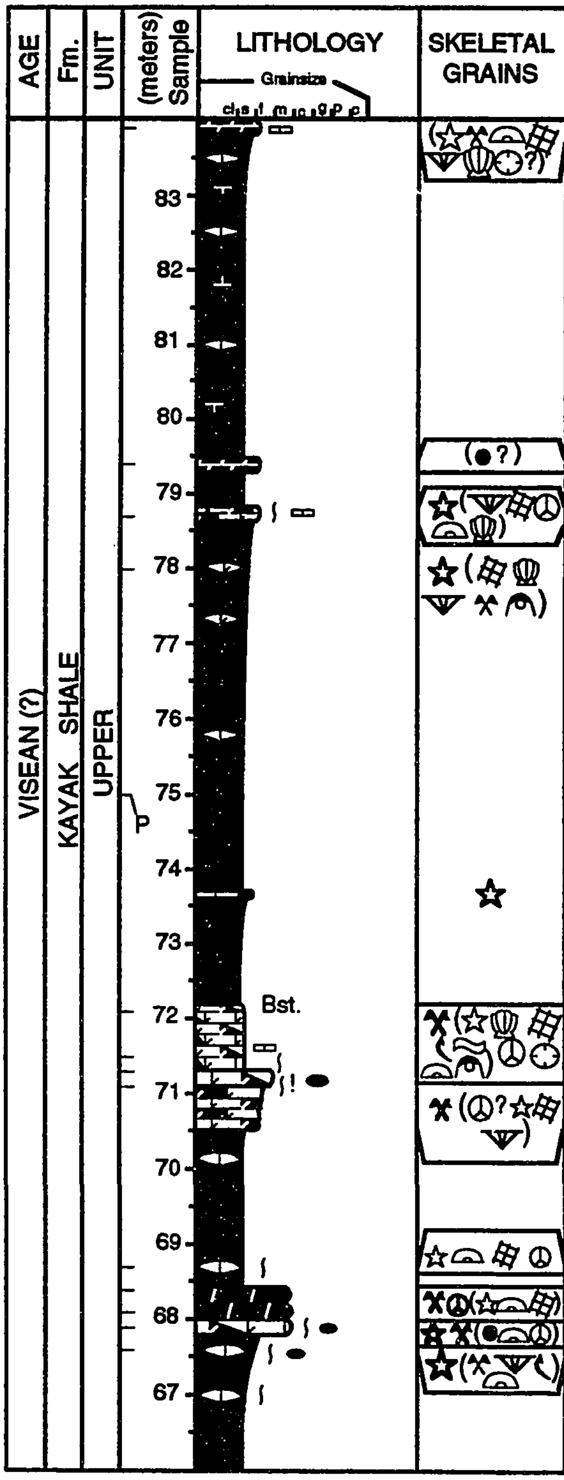
Black fissile mudstone with lenticular-lamina of silty/sandy wackestone/packstone (?). Restricted-platform setting with anaerobic to dysaerobic bottom water condtions. Wackestone/ packstone lamina record authocthonous carbonate debris transported into an inhospitable marine setting, probably by storm-generated currents.

Black fissile shale with orange-brown weathering silty/sandy, lenticular laminated wackestone (?); succession capped by thin- to medium-bedded argillaceous lime mudstone/wackestone; argillaceous material up to 10% of rock. Restricted- to marginally restricted-platform setting with anaerobic to marginally dysaerobic bottom water conditions. Small pelmatozoan buildup within a shale-dominated setting aggraded above anaerobic bottom water layer into a higher marginally dysearobic water layer. Scattered argillaceous material records turbid water conditions, which most likely had a strong inhibiting affect on organic productivity.



REMARKS 89ADL8 p. 3 of 11

Black shale with common poorly preserved plant fragments. Restricted-platform setting with anaerobic bottom water conditions. Deposited in low-energy marine setting, below fairweather wave-base. Common plant fragments indicate a paleogeographic position relatively close to the strand line.



REMARKS

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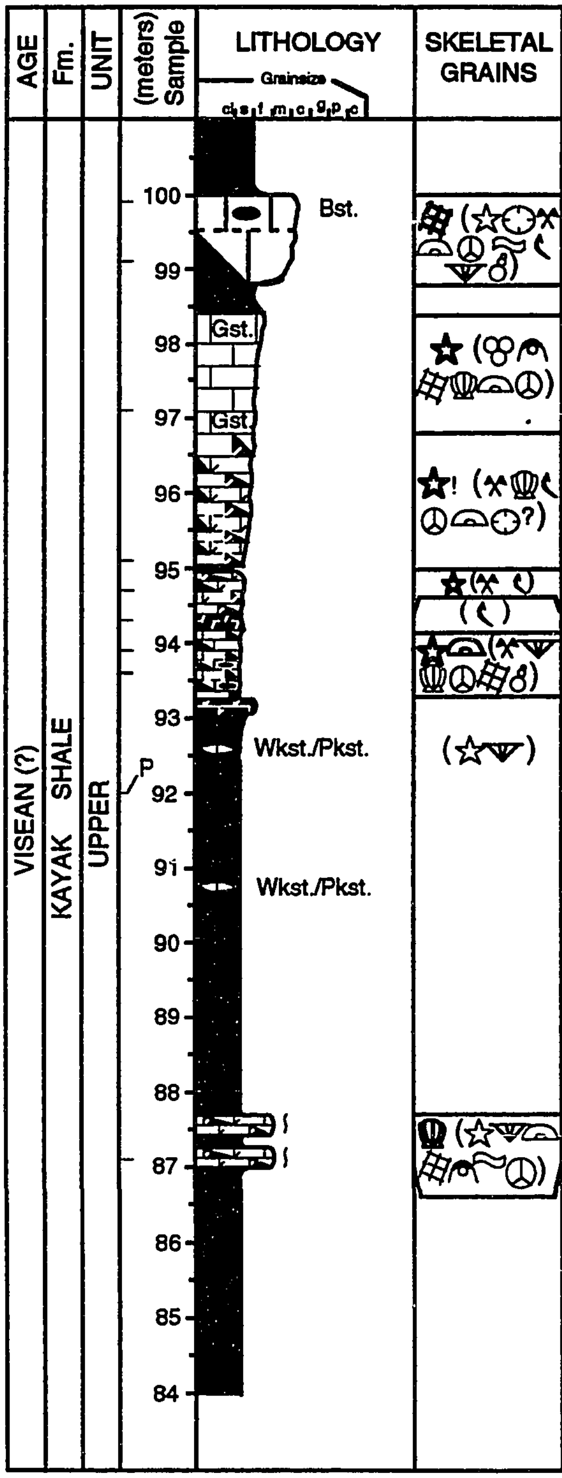
Dolomitic mudstone with ferruginous spiculitc limeclasts; skeletal grains total > 2-3% of interval.

Shale becomes increasingly calc. upsection; limeclasts of micro- and macrodolomite at 78.7 m record strom-wave reworking of partially lithified lime mud substrate.

From 73 to 84 m the section consists of black shale with several thickening-upward successions capped by red-brown weathering wackestone and dolomitic mudstone. Restricted-platfrom setting with anaerobic bottom water layer, below fairweather wave-base. Repeated development of small carbonate buildups within an overall shale-dominated setting. These thin thickening-upward successions record a patchwork mosaic of isolated buildups separated by deeper water areas where anaerobic conditions prevailed and terrigenous mud was slowly accumulating.

Red-brown weathering, thin- to thick-bedded; argillaceous material up to 20% of rock; *Syringipora* corals in growth position (?) at top of interval. Marginally restricted-platform setting with dysaerobic bottom water layer. Small buildup shoaled to relatively shallow depths(<25 m?) in turbid water, shale-dominated setting. Enclosing shale records prevailing anaerobic bottom water conditons.

Dark gray weathering, siliceous packstone and dolomitic mudstone. Depositional setting similar to wackestone and boundstone from 70.5 to 72 m.



REMARKS

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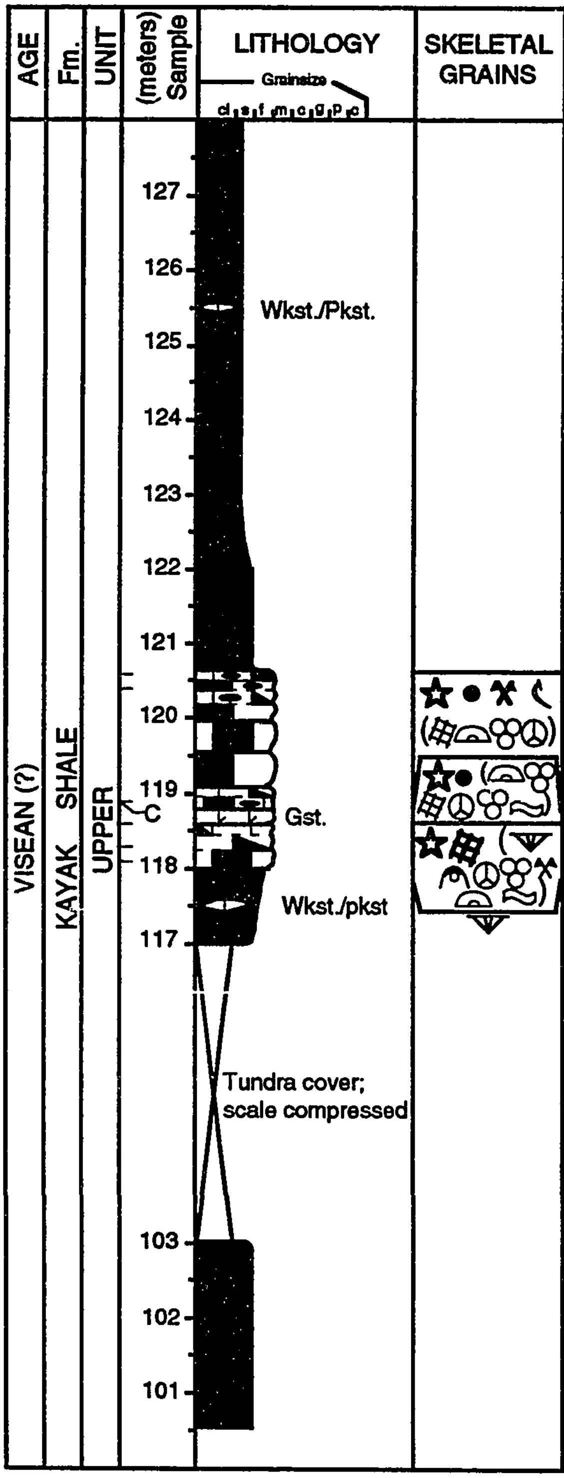
Orange-brown weathering wackestone, packstone, and grainstone; thin- to thick-bedded, thin beds are wavy; abundant thin interbeds of black non-calc. shale. Open-platform setting. Grainstone and boundstone near top indicate buildup shoaled to relatively shallow water - above fairweather wave-base (4-6 m for protected settings; Flugel, 1982). Faunal assemblage indicate normal marine salinity and dissolved oxygen levels. Abundant interbeds of non-calc. shale throughout interval indicate that carbonate production was interrupted by periodic influxes of terrigenous mud, probably due to storm and/or major terrestrial flood events.

Black calc. shale/mudstone with lenticular-lamina orange-brown weathering wackestone/packstone; shale with common thin pyritic beds and ovoid-shaped pyritic siltstone concretions; scolecodonts at 92 m (Utting, 1990). Restricted-platform setting, below fariweather wave-base with anaerobic bottom water conditions.

89ADL8
p. 6 of 11

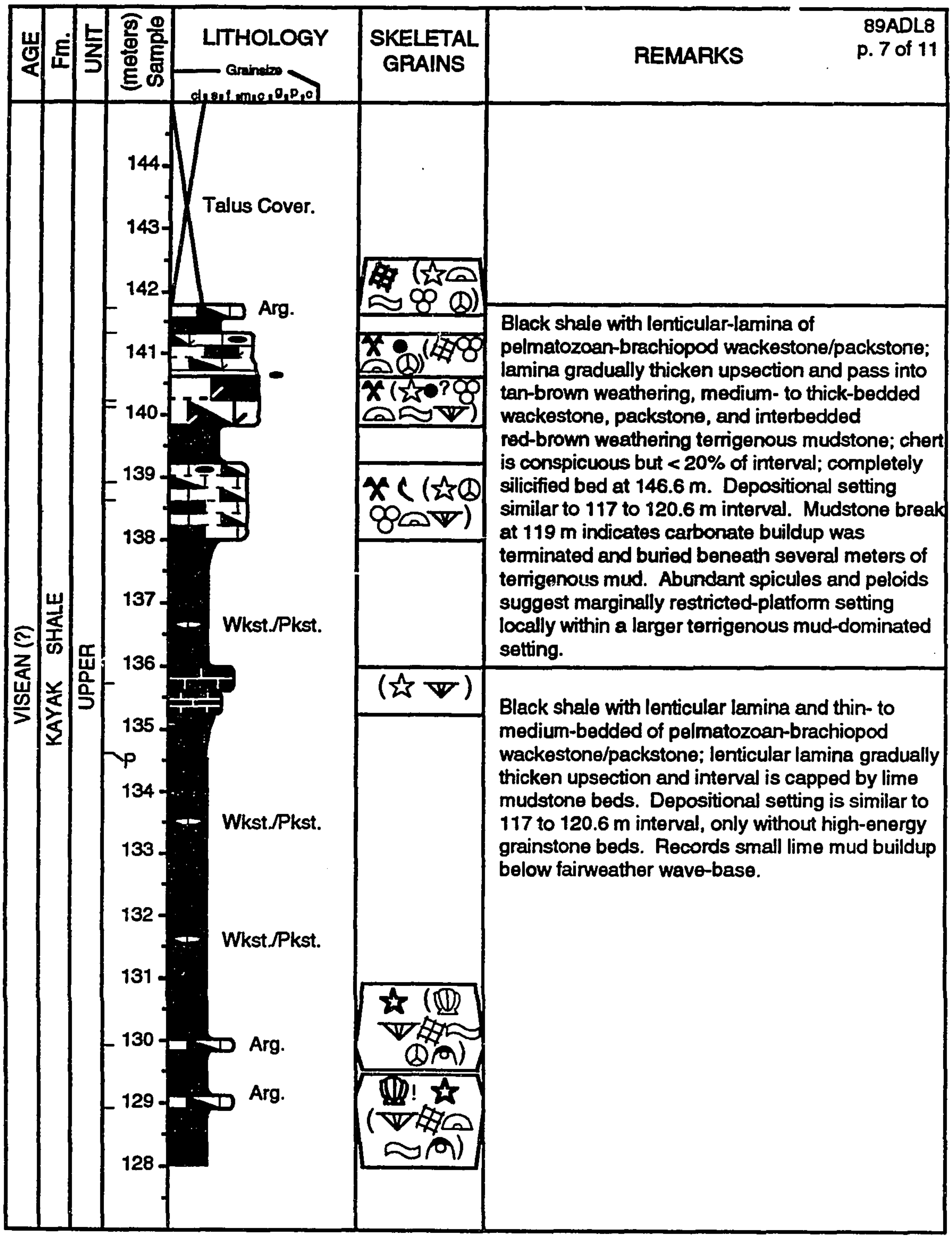


REMARKS

Dark gray to red-brown weathering shale with abundant lenticular -amina of pelmatozoan-brachiopod wackestone/packstone; some wackestone/packstone lamina have abundant pelecypod (?) impressions. Restricted- to marginally restricted (?)-platform setting, below fairweather wave-base. Close association with black shale suggest anaerobic. Wackestone/ packstone lamina were probably deposited during times of improved circulation.

Red-brown weathering mudstone. Restricted-platform setting with anaerobic bottom water layer, below fairweather wave-base.

Red-brown weathering shale; common small-scale folds; some thin to thick lamina of brachiopod wackestone/packstone above covered interval. Shale with interlaminated wackestone/packstone pass upward into interbedded light to dark gray weathering argillaceous wackestone and packstone, thin- to thick- bedded; common shale drapes. Mraginally restricted- to open-platform setting. Records development of buildup within an overall shale-dominated setting with anaerobic bottom water conditions. Buildup aggraded into marginally dysaerobic to aerobic water layers. The grainstone bed may record shoaling to intertidal depths, or winnowing of lime mud by storm-generated waves. Shale drapes indicate periodic influxes of terrigenous mud, probably related to fluvial flood and/or oceanic storm events. Argillaceous wackestone/packstone indicate turbid water conditions.


AGE
Fm.
UNIT
(meters)
Sample
LITHOLOGY
Grainsize
SKELETAL GRAINS
REMARKS
89ADL8
p. 7 of 11
VISEAN (?)
KAYAK SHALE
UPPER
144
143
142
141
140
139
138
137
136
135
134
133
132
131
130
129
128
Talus Cover.
Arg.
Wkst./Pkst.
Wkst./Pkst.
Wkst./Pkst.
Arg.
Arg.
P
Black shale with lenticular-lamina of pelmatozoan-brachiopod wackestone/packstone; lamina gradually thicken upsection and pass into tan-brown weathering, medium- to thick-bedded wackestone, packstone, and interbedded red-brown weathering terrigenous mudstone; chert is conspicuous but < 20% of interval; completely silicified bed at 146.6 m. Depositional setting similar to 117 to 120.6 m interval. Mudstone break at 119 m indicates carbonate buildup was terminated and buried beneath several meters of terrigenous mud. Abundant spicules and peloids suggest marginally restricted-platform setting locally within a larger terrigenous mud-dominated setting.
Black shale with lenticular lamina and thin- to medium-bedded of pelmatozoan-brachiopod wackestone/packstone; lenticular lamina gradually thicken upsection and interval is capped by lime mudstone beds. Depositional setting is similar to 117 to 120.6 m interval, only without high-energy grainstone beds. Records small lime mud buildup below fairweather wave-base.

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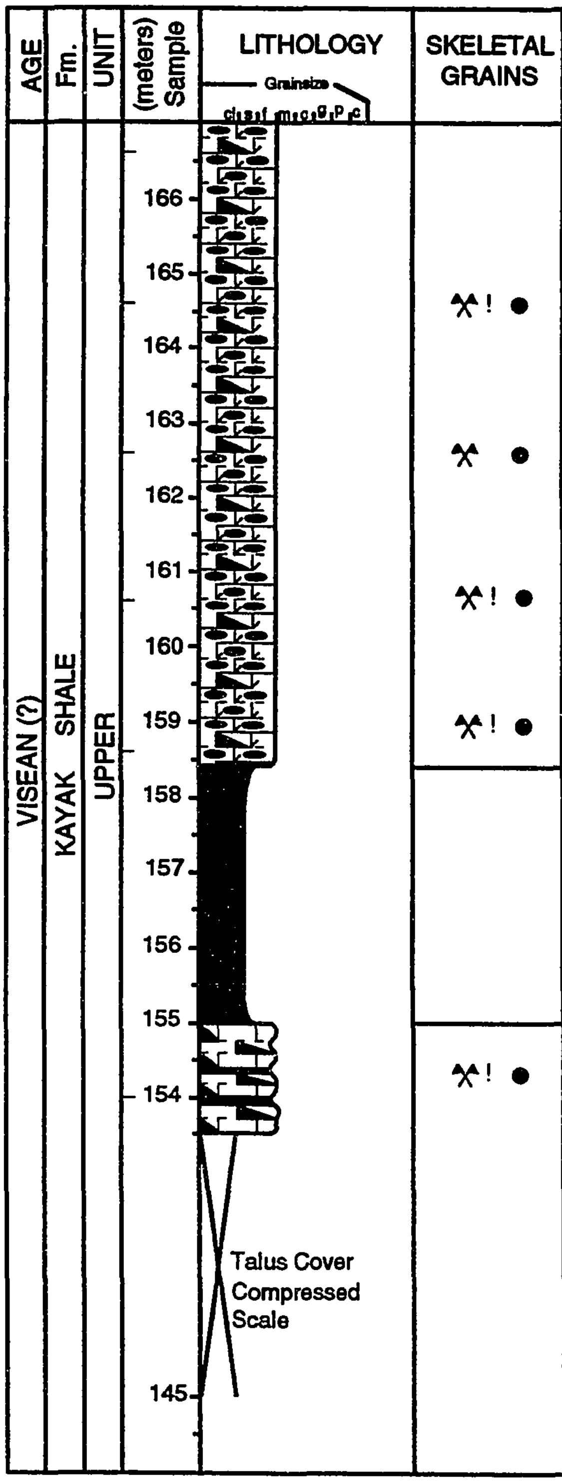
p. 8 of 11



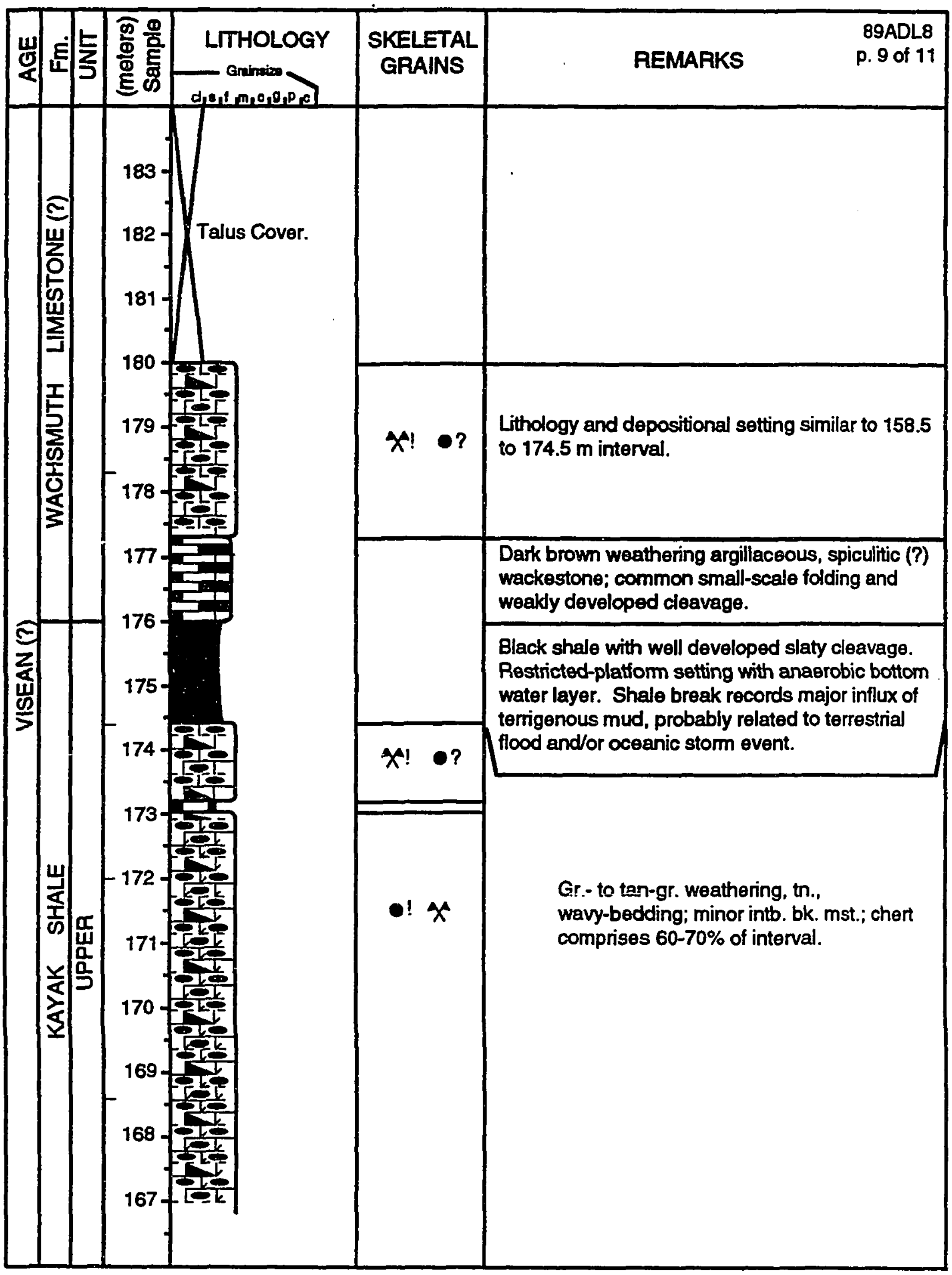
REMARKS

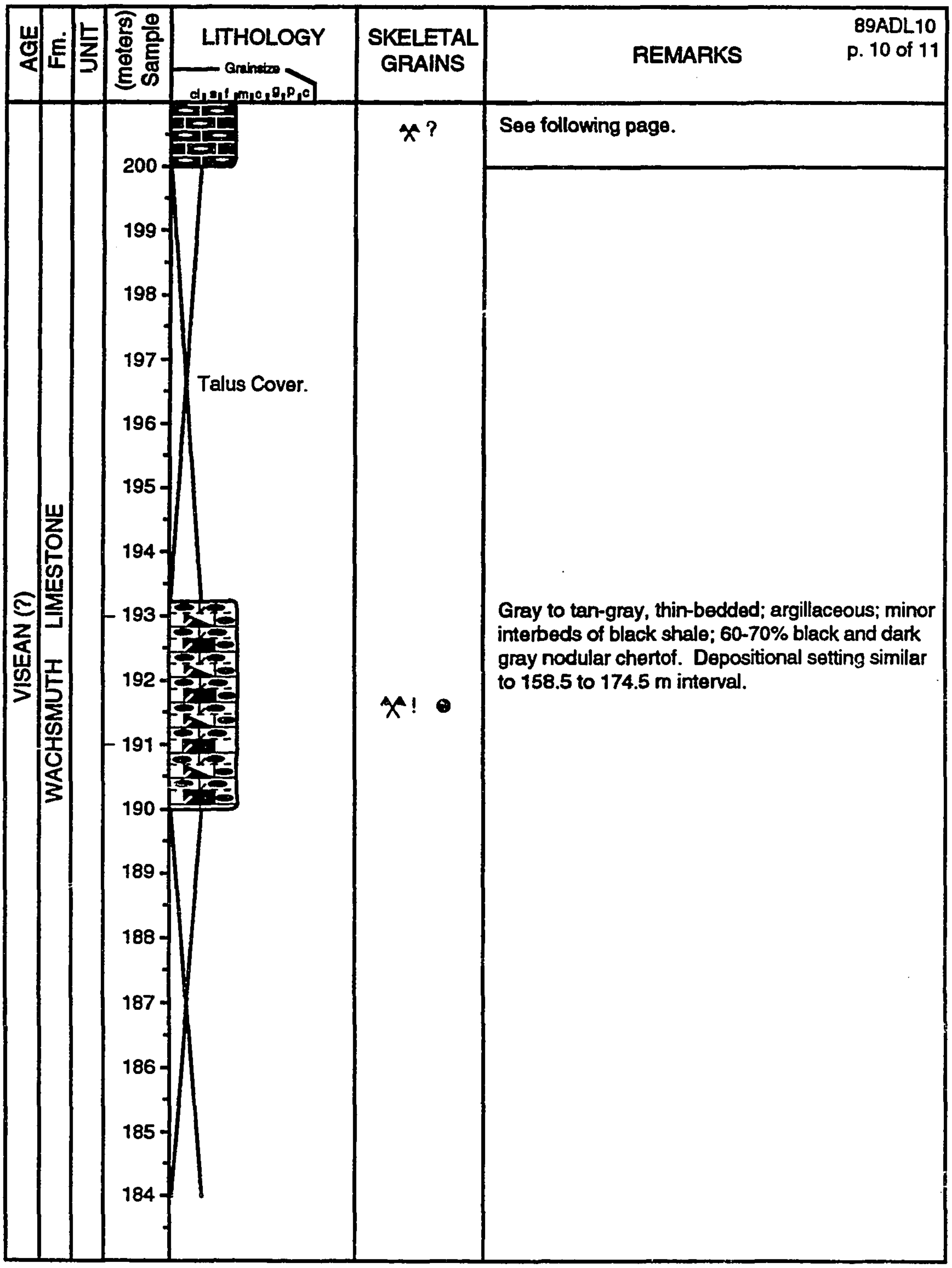
Several upright tight-to-isoclinal folds (outcrop-scale) are present between 158 m and 180 m.

Dark gray to red-brown weathering argillaceous packstone from 153.5-174.4 m; up to 70% chert in bed-parallel nodules. Marginally restricted-platform setting with slightly dysaerobic bottom water conditions, below fairweather wave-base. Records buildup of siliceous sponges within a terrigenous mud-dominated setting. Shale interbeds indicate periodic influxes of terrigenous mud, possibly from fluvial flood events. Alternatively, shale interbeds and partings could record periodic storms which stirred the sea floor and put mud into suspension, thus blanketing the spiculitic/ peloidal packstone buildup from time to time.

Red-brown and black weathering shale. Restricted-platform setting with anaerobic bottom water layer, below fairweather wave-base.

Interbedded dark gray packstone and black terrigenous mudstone; packstone is thin-bedded. Marginally restricted-platform setting with dysaerobic bottom water layer, below fairwsather wave-base


AGE
Fm.
UNIT
(meters) Sample
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
89ADL8
p. 9 of 11
VISEAN (?)
WACHSMUTH LIMESTONE (?)
KAYAK SHALE
UPPER
183
182
181
180
179
178
177
176
175
174
173
172
171
170
169
168
167
Talus Cover.
Lithology and depositional setting similar to 158.5 to 174.5 m interval.
Dark brown weathering argillaceous, spiculitic (?) wackestone; common small-scale folding and weakly developed cleavage.
Black shale with well developed slaty cleavage. Restricted-platform setting with anaerobic bottom water layer. Shale break records major influx of terrigenous mud, probably related to terrestrial flood and/or oceanic storm event.
Gr.- to tan-gr. weathering, tn., wavy-bedding; minor intb. bk. mst.; chert comprises 60-70% of interval.


AGE
Fm.
UNIT
(meters)
Sample
LITHOLOGY
Grainsize
cl s f m c g p c
SKELETAL GRAINS
REMARKS
89ADL10
p. 10 of 11
See following page.
200
199
198
197
Talus Cover.
196
195
194
193
192
191
190
189
188
187
186
185
184
VISEAN (?)
WACHSMUTH LIMESTONE
?
!
Gray to tan-gray, thin-bedded; argillaceous; minor interbeds of black shale; 60-70% black and dark gray nodular chertof. Depositional setting similar to 158.5 to 174.5 m interval.

89ADL8
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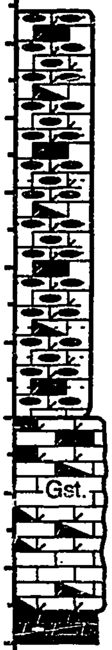
AGE	FORMATION	UNIT	Thickness (meters) Sample Intervals	LITHOLOGY (Grainsize: cl, s, f, m, c, g, p)	SKELETAL GRAINS	REMARKS
			210	Top of Section		Large-scale detachment folds in the overlying Alapah and Wahoo Limestones.
VISEAN (?)	WACHSMUTH LIMESTONE (?)		209–204			Similar lithology and depositional setting as 158.5 to 174.5 m interval. Records drowning of shoal and restablishment of argillaceous spiculitic packstone deposition - sponge buildups below fairweather wave-base.
			204–202 (C at 203)	Gst.; Gst./Bst.		Interbedded dark br. weathering packstone, grainstone, and minor coralline boundstone and wackestone; meddium-bedded. Open-platform setting, above fairweather wave-base. Small shoal the developed above silicesous lime mudstone.
			201			Gray to tan gray weathering siliceous lime mudstone; thin-bedded; up to 70% chert nodules; rare abraded pelmatozoan fragments. Marginally restricted-platform, below fairweather wave-base.

1990 MEASURED SECTION SYMBOL KEY

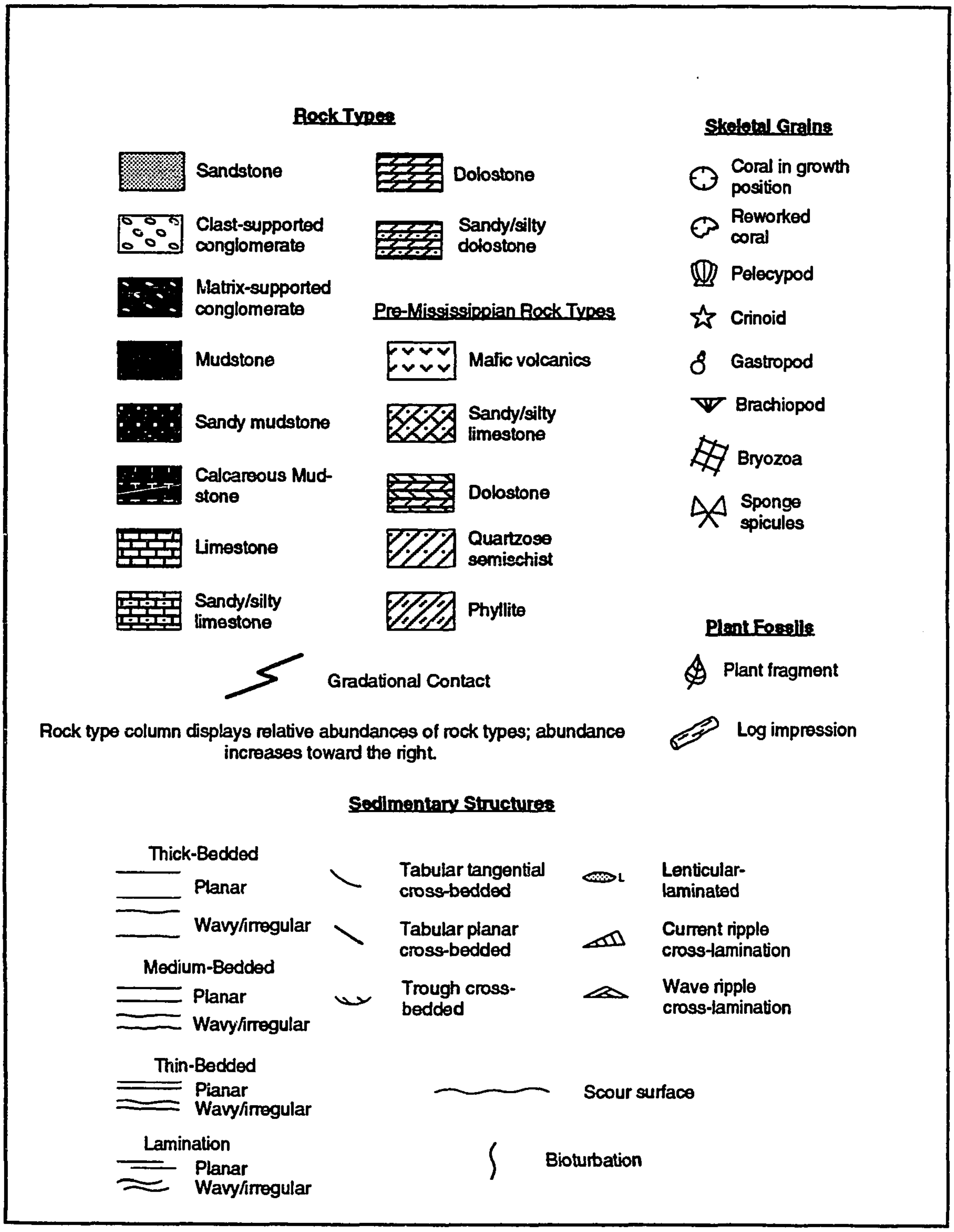
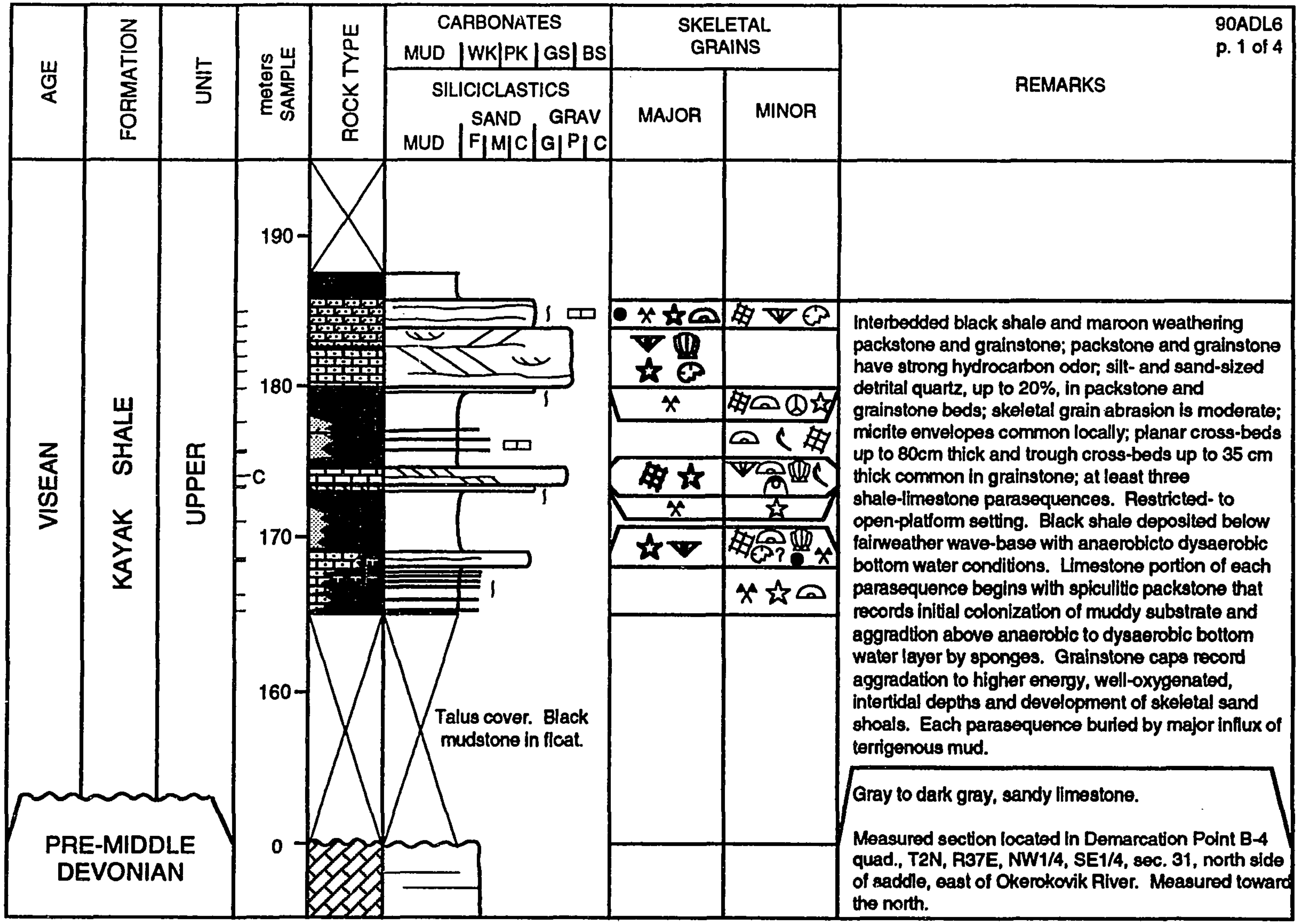
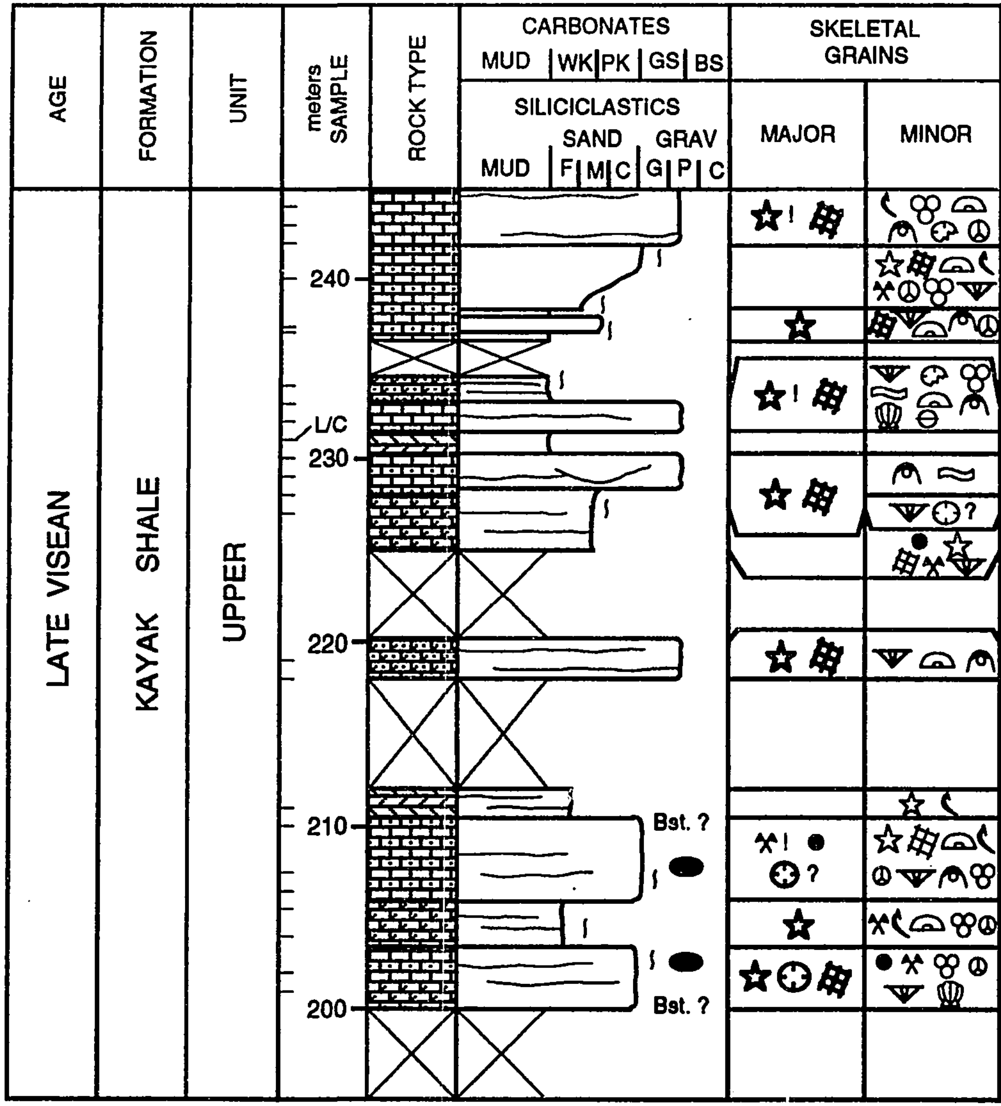


Figure F-2 - Key to symbols used in measured sections obtained during the 1990 field season.



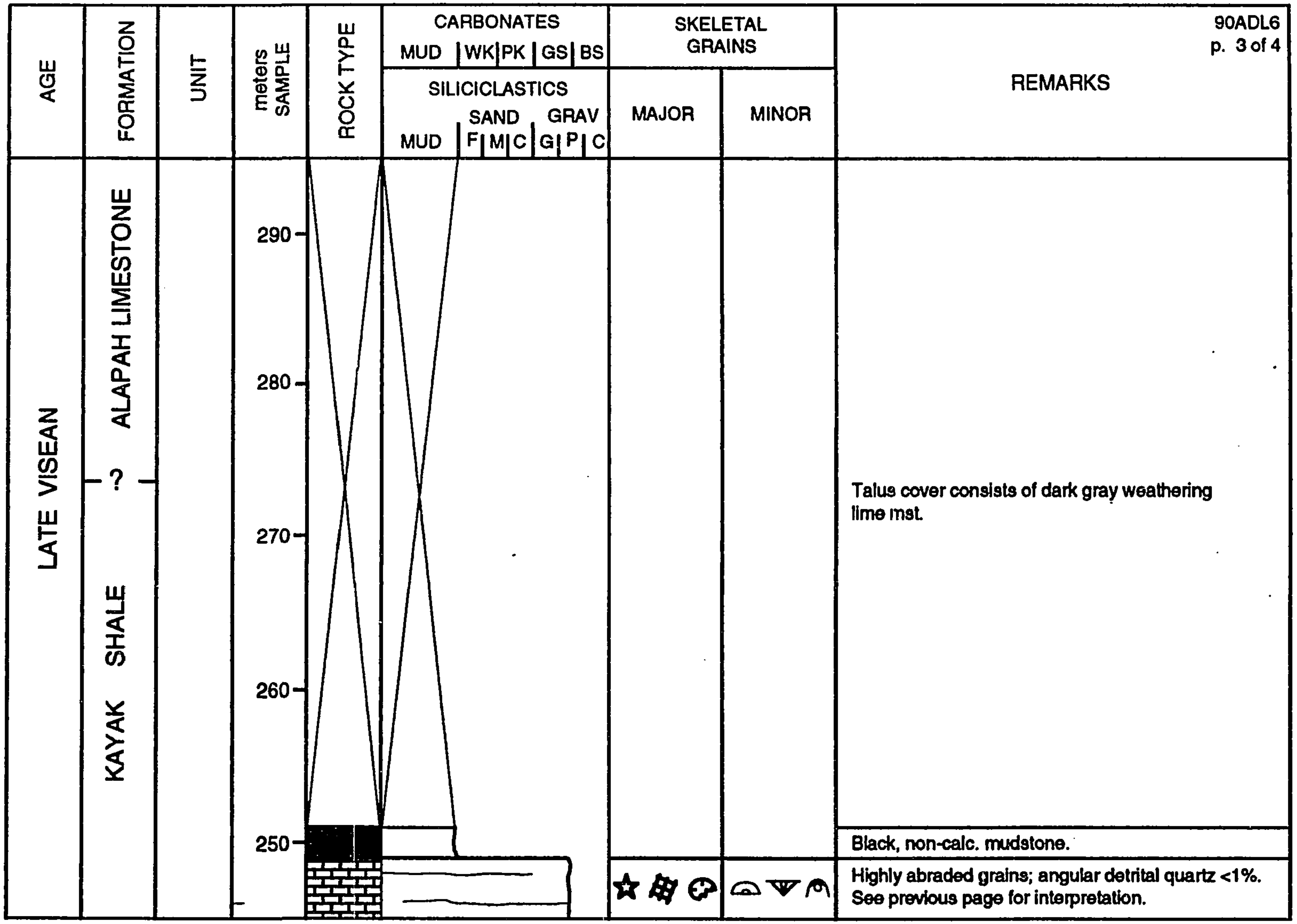
90ADL6
p. 1 of 4
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
MUD SAND F M C GRAV G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
VISEAN
KAYAK SHALE
UPPER
PRE-MIDDLE DEVONIAN
190
180
C
170
160
0
Talus cover. Black mudstone in float.
Interbedded black shale and maroon weathering packstone and grainstone; packstone and grainstone have strong hydrocarbon odor; silt- and sand-sized detrital quartz, up to 20%, in packstone and grainstone beds; skeletal grain abrasion is moderate; micrite envelopes common locally; planar cross-beds up to 80cm thick and trough cross-beds up to 35 cm thick common in grainstone; at least three shale-limestone parasequences. Restricted- to open-platform setting. Black shale deposited below fairweather wave-base with anaerobicto dysaerobic bottom water conditions. Limestone portion of each parasequence begins with spiculitic packstone that records initial colonization of muddy substrate and aggradtion above anaerobic to dysaerobic bottom water layer by sponges. Grainstone caps record aggradation to higher energy, well-oxygenated, intertidal depths and development of skeletal sand shoals. Each parasequence buried by major influx of terrigenous mud.
Gray to dark gray, sandy limestone.
Measured section located in Demarcation Point B-4 quad., T2N, R37E, NW1/4, SE1/4, sec. 31, north side of saddle, east of Okerokovik River. Measured toward the north.

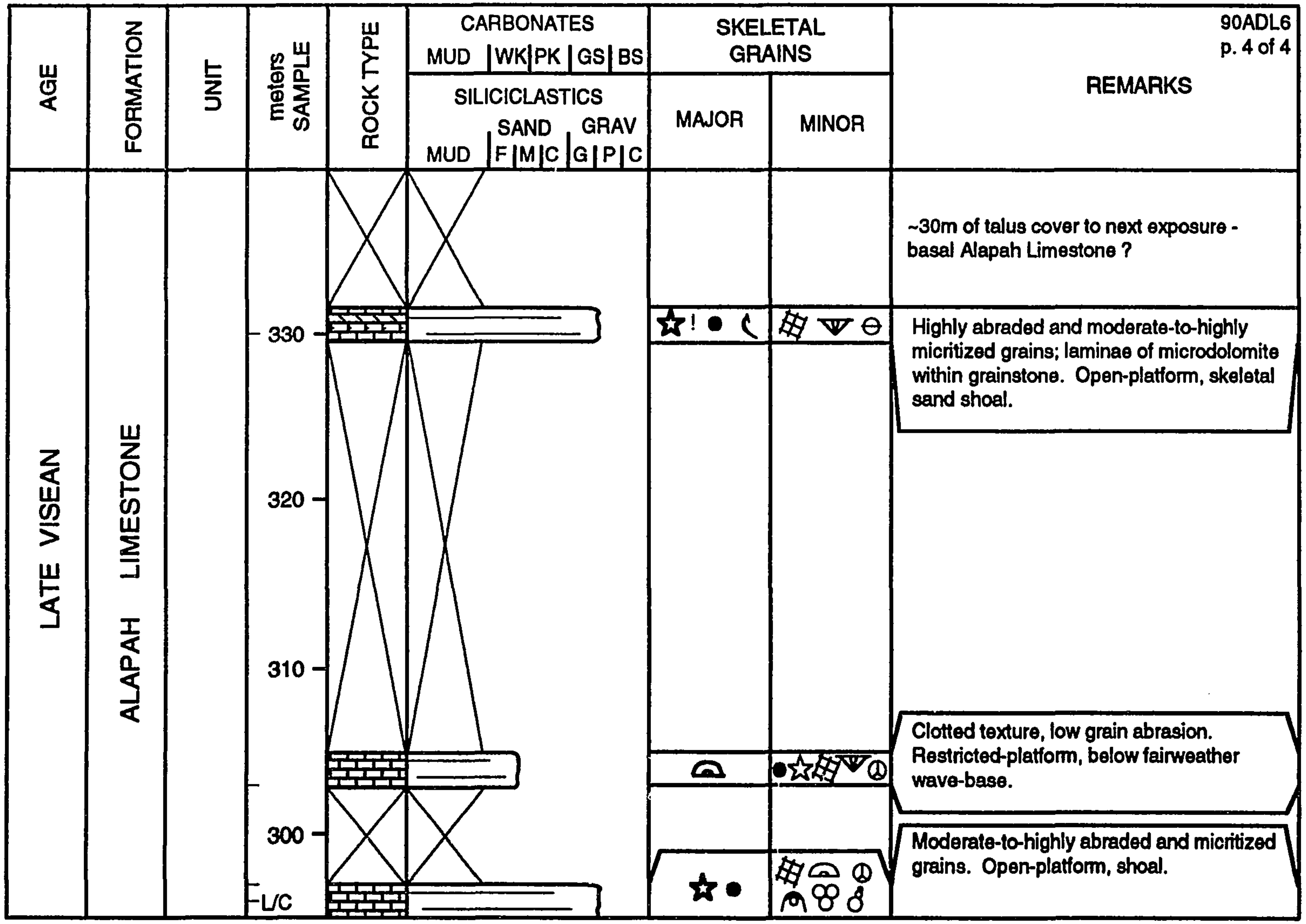


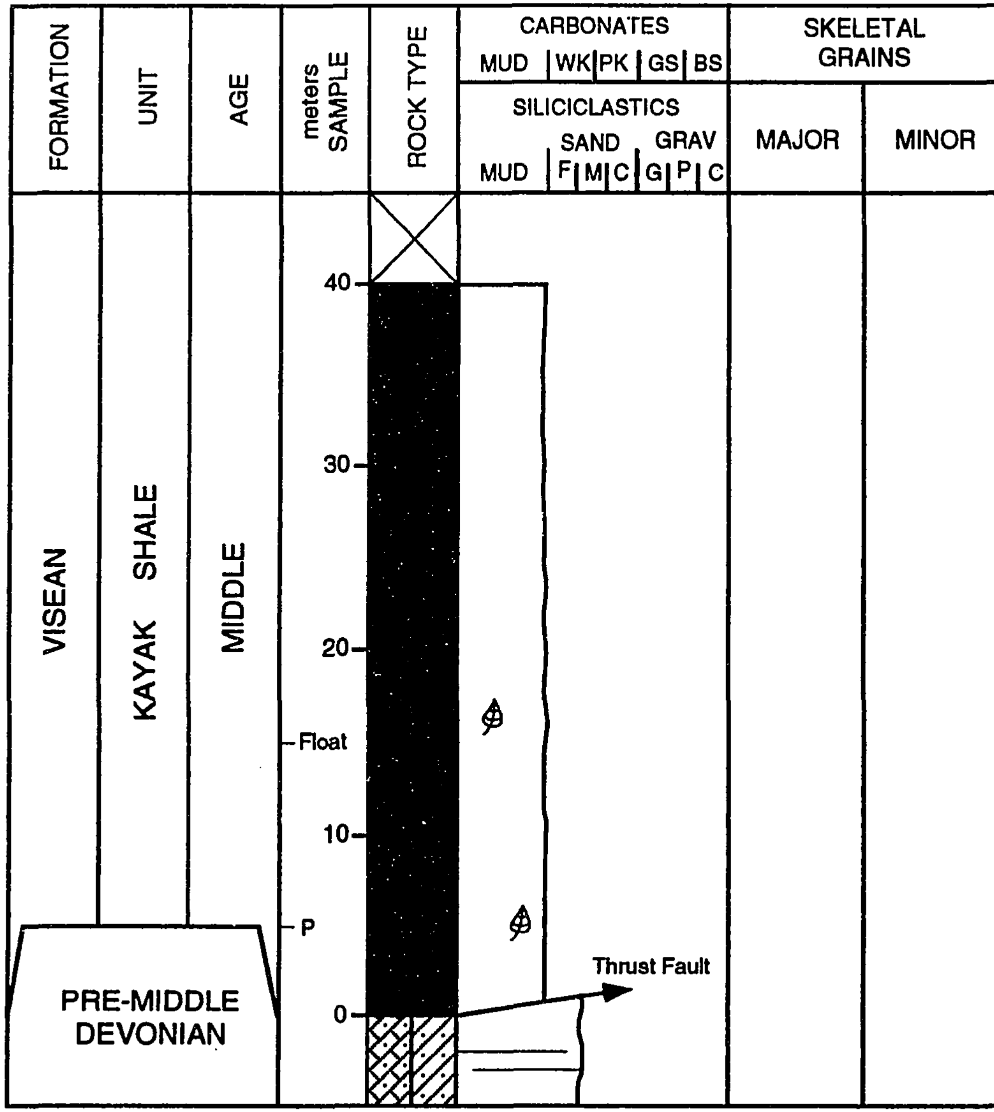
90ADL6
p. 2 of 4

REMARKS

200 - 249 m
Maroon weathering lime mudstone, packstone, grainstone, and minor dolomitic mudstone and *Syringipora* boundstone; packstone and dolomitic mudstone have up to 10% silt- and sand-sized detrital quartz near base of interval, quartz content gradually decreases toward top of interval; possible evaporite pseudomorphs at 211 m; low-relief scour surfaces up to 3 m across are common in grainstone beds; contacts are generally sharp, however, lime mudstone passes gradually and progressively upsection into wackestone and packstone from 239 to 242 m. Exposure quality is variable, which makes delineation of parasequences difficult. Uppermost 10 m of interval consists of wackestone-packstone parasequence that is capped by thick grainstone succession. Restricted- to open-platform setting. Dolomitic mudstone is unfossiliferous or sparsely fossiliferous, which suggests deposition in a restricted-platform setting, below fairweather wave-base, or in a tidal flat setting. No other diagnostic features are present to provide a more precise interpretation. Packstone records deposition in marginally restricted- to open-platform settings, near fairweather wave-base, or on lee side of shoals. Grainstone records deposition as skeletal sand shoals. The dominance of sharp contacts between lithologies in the lower 2/3 of the interval suggests an acyclic succession. This succession may have been deposited in a setting with a variety of environments in close proximity - each characterized by a slight difference in elevation - creating a facies mosaic (e.g. Laporte, 1967).


90ADL6
p. 3 of 4
AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
LATE VISEAN
ALAPAH LIMESTONE
?
KAYAK SHALE
290
280
270
260
250
Talus cover consists of dark gray weathering lime mst.
Black, non-calc. mudstone.
Highly abraded grains; angular detrital quartz <1%. See previous page for interpretation.


90ADL6
p. 4 of 4
AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD | WK | PK | GS | BS
SILICICLASTICS
SAND
GRAV
MUD | F | M | C | G | P | C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
LATE VISEAN
ALAPAH LIMESTONE
330
320
310
300
L/C
~30m of talus cover to next exposure - basal Alapah Limestone ?
Highly abraded and moderate-to-highly micritized grains; laminae of microdolomite within grainstone. Open-platform, skeletal sand shoal.
Clotted texture, low grain abrasion. Restricted-platform, below fairweather wave-base.
Moderate-to-highly abraded and micritized grains. Open-platform, shoal.



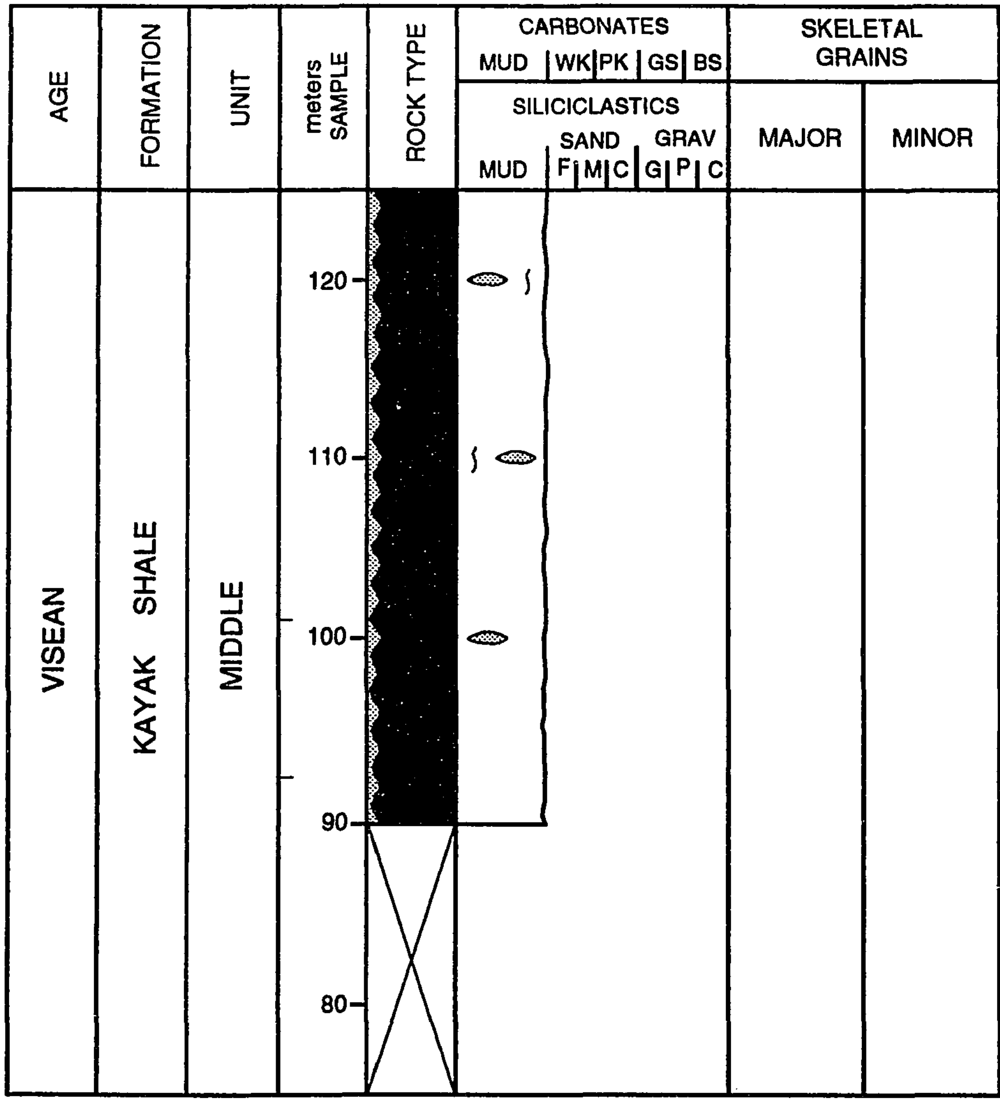
90ADL10
p. 1 of 6

REMARKS

Black fissile silty shale; silty shale near base of section passes along strike toward the west into mudstone with abundant small, broken plant fragments; very coarse-grained sandstone in float at 30 m, no exposures of this lithology. Plant fragments near base suggest that fault only removed the basal beds of Kayak and Kekiktuk Conglomerate (if depositionally present). Deposited in shallow-marine setting, below fairweather wave-base and an anaerobic to dysaerobic bottom water layer.

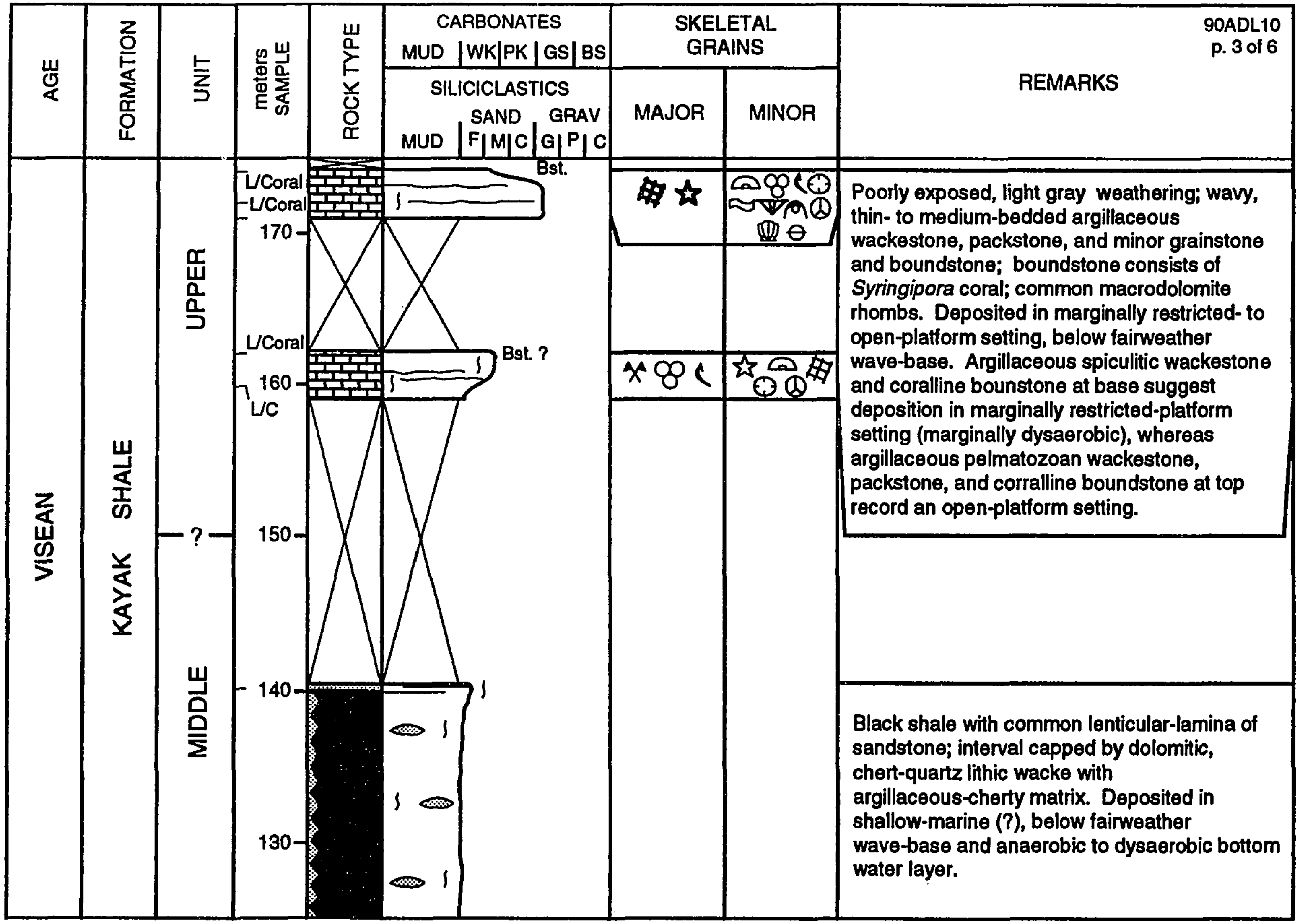
Dark gray weathering, quartzose limestone and light gray-to-tan weathering quartz semi-schist.

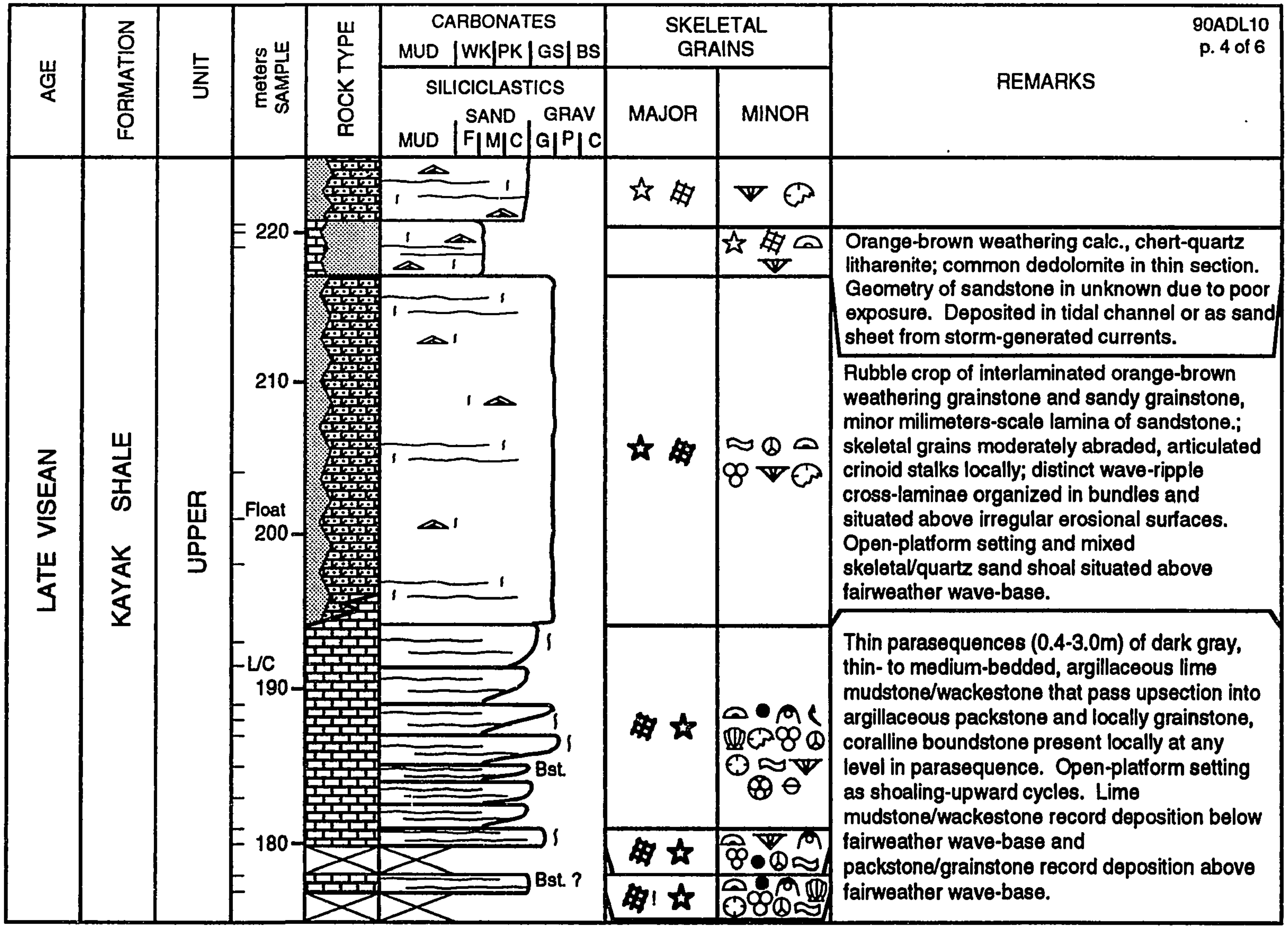
Measured section located in Demarcation Point C-3 quad., T2N, R39E, NE1/4, NE1/4, sec. 12 and SE1/4, SE1/4, sec. 1. Started measuring on north side of saddle east of Redwacke Creek and proceeded toward the north, up south-facing slope to crest and down the north side to Kayak-Alapah contact.



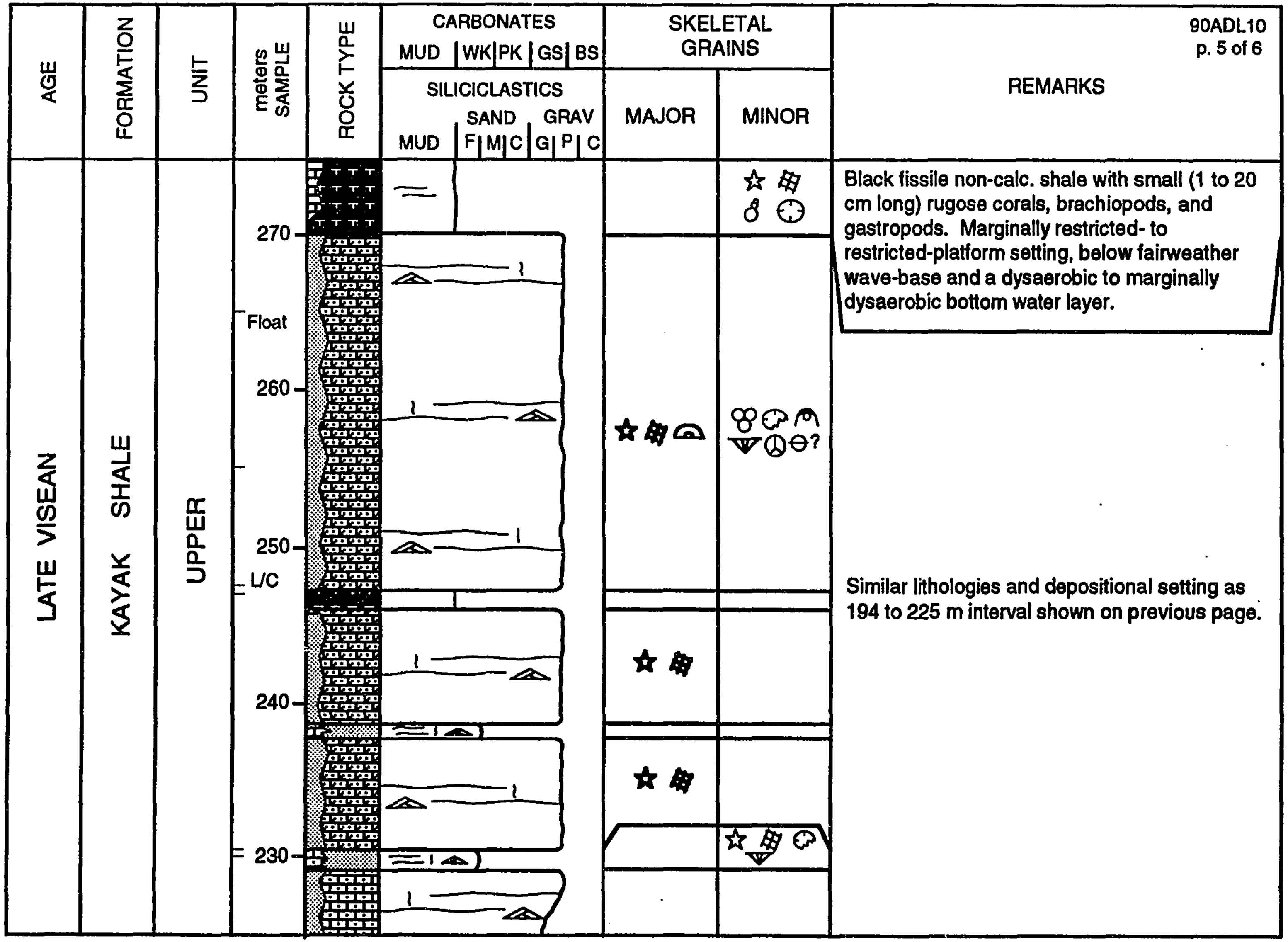
REMARKS

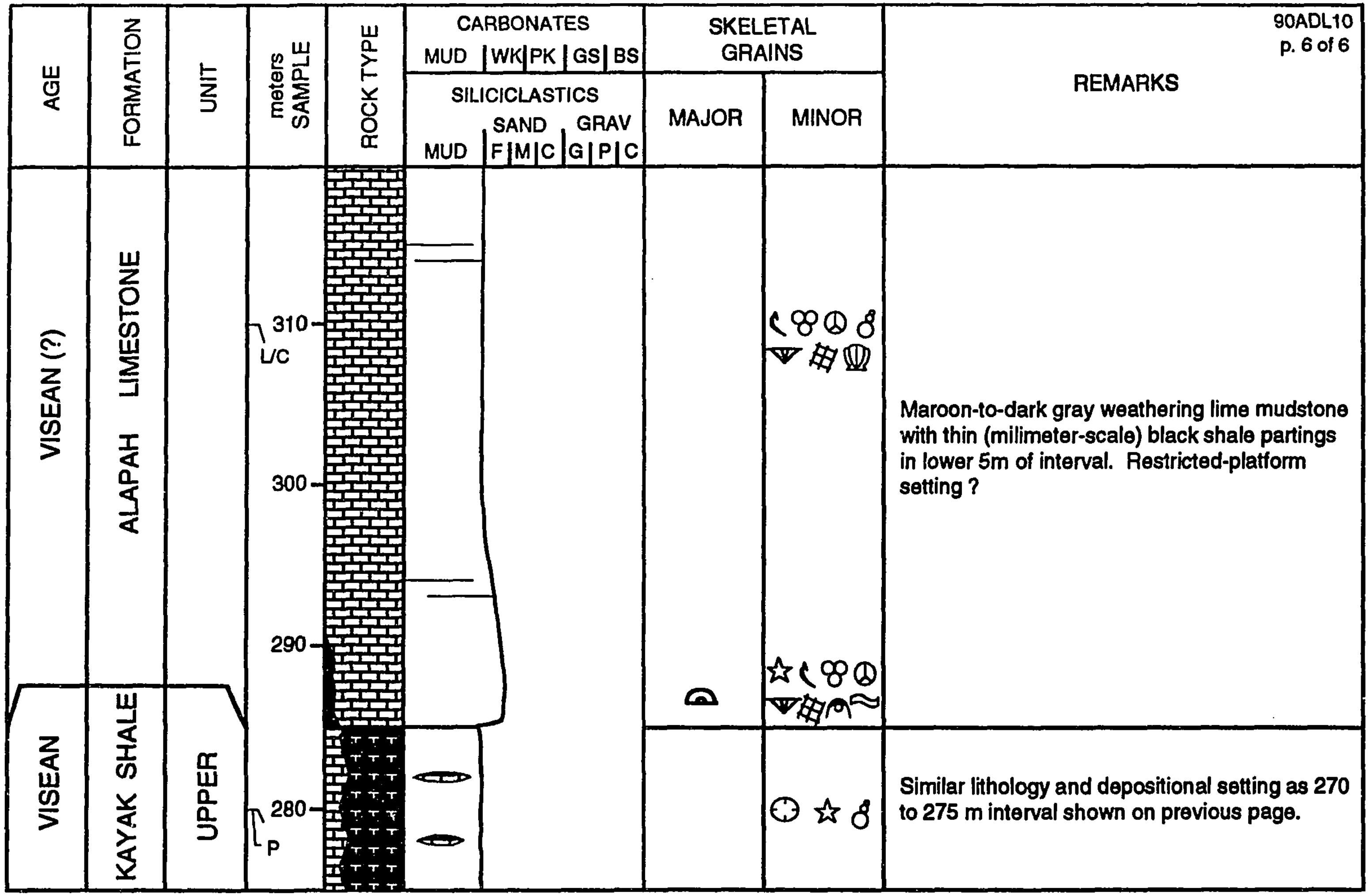
Black to dark gray silty shale with common lenticular lamina of argillaceous moderately bioturbated sandstone. Deposited in shallow marine (?) setting, below fairweather wave-base and dysaerobic bottom water layer. Bioturbated sandstone may record temporary increases in dissolved oxygen content of bottom water (from anaerobic to dysaerobic conditions) due to storm-generated currents.

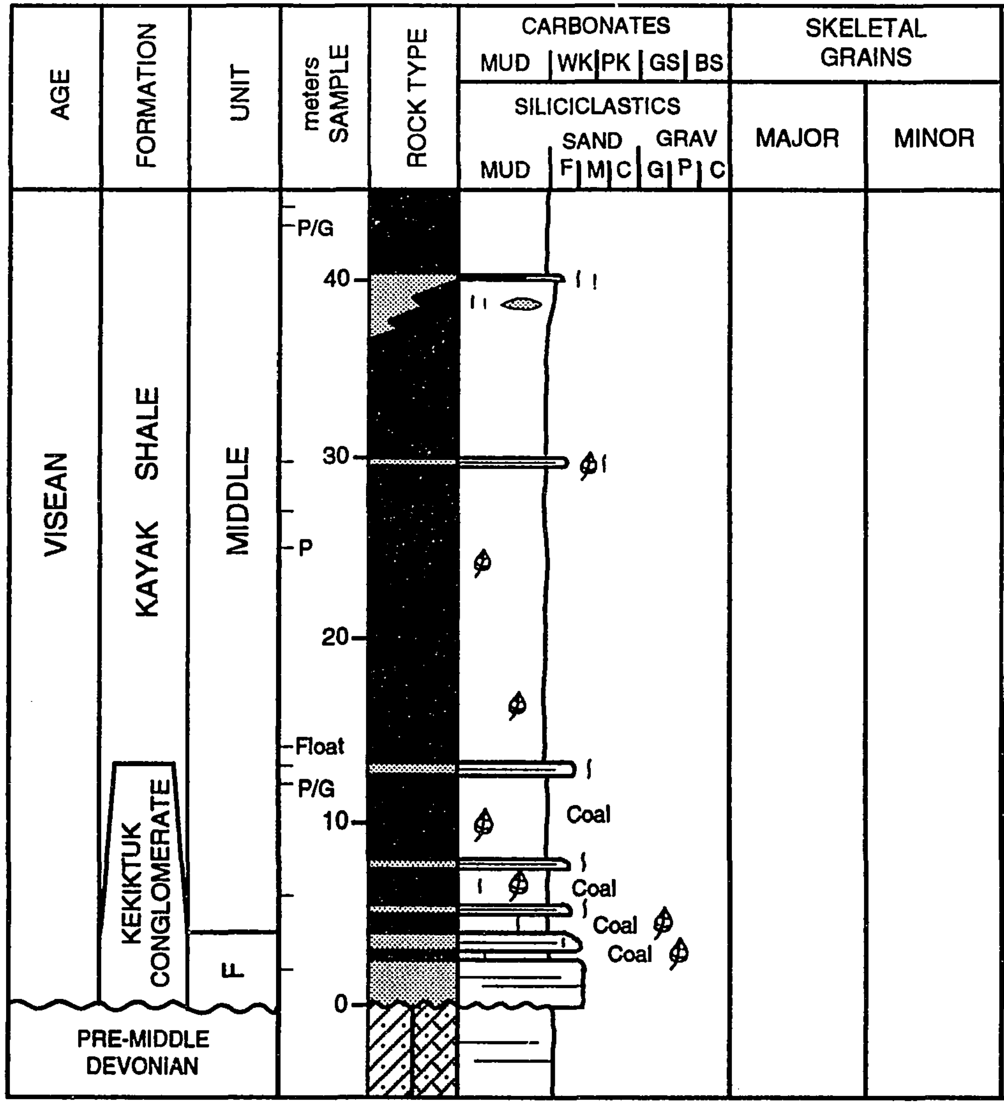

AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
90ADL10
p. 3 of 6
VISEAN
KAYAK SHALE
UPPER
?
MIDDLE
L/Coral
L/Coral
L/Coral
L/C
170
160
150
140
130
Bst.
Bst. ?
Poorly exposed, light gray weathering; wavy, thin- to medium-bedded argillaceous wackestone, packstone, and minor grainstone and boundstone; boundstone consists of *Syringipora* coral; common macrodolomite rhombs. Deposited in marginally restricted- to open-platform setting, below fairweather wave-base. Argillaceous spiculitic wackestone and coralline bounstone at base suggest deposition in marginally restricted-platform setting (marginally dysaerobic), whereas argillaceous pelmatozoan wackestone, packstone, and corralline boundstone at top record an open-platform setting.
Black shale with common lenticular-lamina of sandstone; interval capped by dolomitic, chert-quartz lithic wacke with argillaceous-cherty matrix. Deposited in shallow-marine (?), below fairweather wave-base and anaerobic to dysaerobic bottom water layer.



AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD | WK | PK | GS | BS
SILICICLASTICS
SAND
GRAV
MUD | F | M | C | G | P | C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
90ADL10
p. 4 of 6
LATE VISEAN
KAYAK SHALE
UPPER
220
210
Float
200
L/C
190
180
Bst.
Bst. ?
Orange-brown weathering calc., chert-quartz litharenite; common dedolomite in thin section. Geometry of sandstone in unknown due to poor exposure. Deposited in tidal channel or as sand sheet from storm-generated currents.
Rubble crop of interlaminated orange-brown weathering grainstone and sandy grainstone, minor milimeters-scale lamina of sandstone.; skeletal grains moderately abraded, articulated crinoid stalks locally; distinct wave-ripple cross-laminae organized in bundles and situated above irregular erosional surfaces. Open-platform setting and mixed skeletal/quartz sand shoal situated above fairweather wave-base.
Thin parasequences (0.4-3.0m) of dark gray, thin- to medium-bedded, argillaceous lime mudstone/wackestone that pass upsection into argillaceous packstone and locally grainstone, coralline boundstone present locally at any level in parasequence. Open-platform setting as shoaling-upward cycles. Lime mudstone/wackestone record deposition below fairweather wave-base and packstone/grainstone record deposition above fairweather wave-base.


AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
90ADL10
p. 5 of 6
LATE VISEAN
KAYAK SHALE
UPPER
270
Float
260
250
L/C
240
230
Black fissile non-calc. shale with small (1 to 20 cm long) rugose corals, brachiopods, and gastropods. Marginally restricted- to restricted-platform setting, below fairweather wave-base and a dysaerobic to marginally dysaerobic bottom water layer.
Similar lithologies and depositional setting as 194 to 225 m interval shown on previous page.


90ADL10
p. 6 of 6
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
VISEAN (?)
ALAPAH LIMESTONE
310
L/C
300
290
280
P
VISEAN
KAYAK SHALE
UPPER
Maroon-to-dark gray weathering lime mudstone with thin (milimeter-scale) black shale partings in lower 5m of interval. Restricted-platform setting ?
Similar lithology and depositional setting as 270 to 275 m interval shown on previous page.



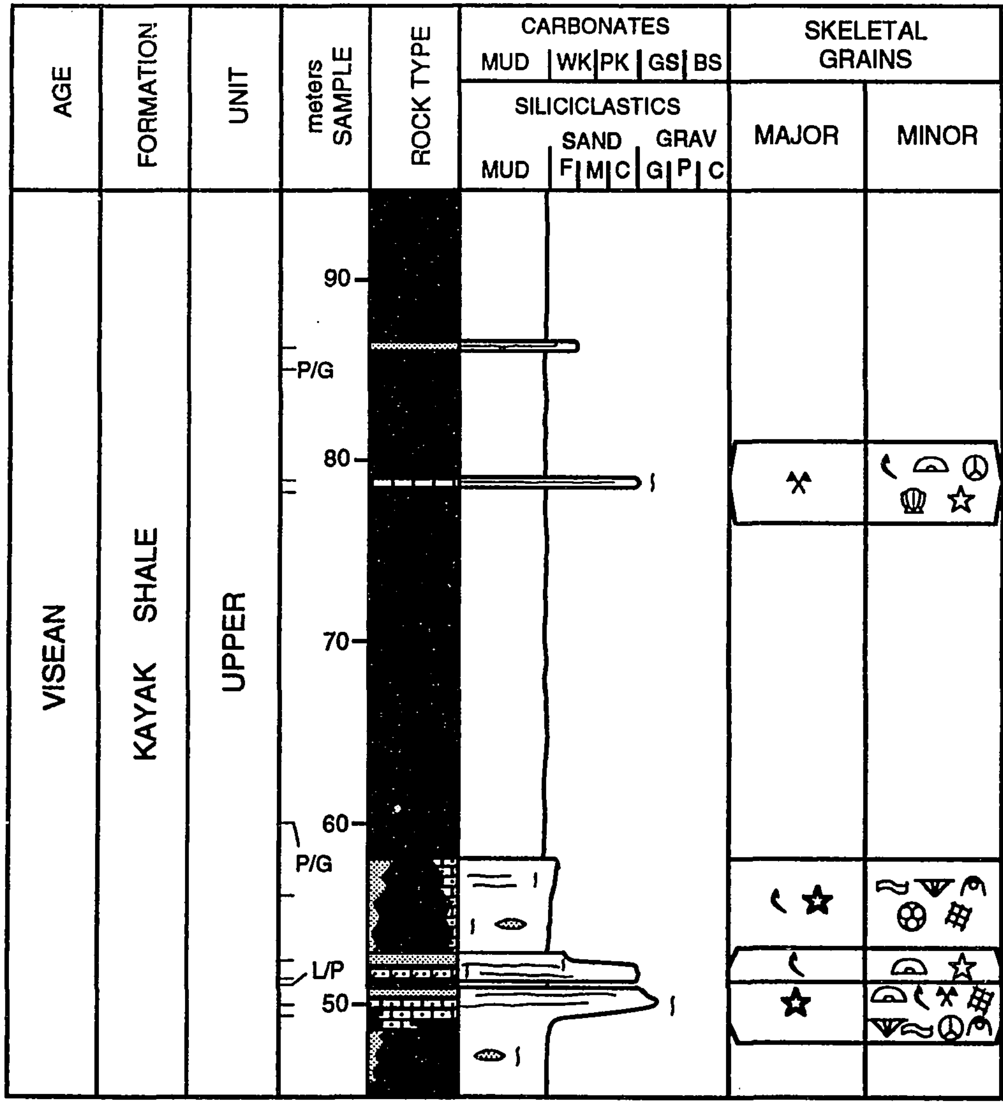
REMARKS

Black to dark gray silty shale with small, poorly preserved plant fragments.; some poorly exposed beds of argillaceous fine-grained sandstone; carbonaceous plant frags. in thin section. Deposited in marginal- to shallow marine setting, below fairweather wave-base and an anerobic bottom water layer.

White-to gray-white weathering chert-quartz litharenite and quartz arenite; sandstone pass upsection into interbedded white and light gray burrow-mottled sandstone and black organic-rich mudstone; mundstone with variably preserved plant fragments up to 30 cm long; minor small log impressions and common anthracitic coal lamina and beds up to 5 cm thick. Deposited in tidal sand flat and associated coastal swamp setting. Sandstone at base of section record unconfined sheet-flood deposits.

Gold-brown weathering quartz semischist and sandy limestone; limestone is Ordovician (?) (Reiser et al., 1980).

Measured section located in Demarcation Point B-1 quad., T1N, R45E, NE1/4, SE1/4, sec. 28, in saddle west of Clarence River. Started measuring on south side of saddle in rubble-crop of Kekiktuk Conglomerate and proceeded toward the north, across saddle and up north side to base of Alapah Limestone.



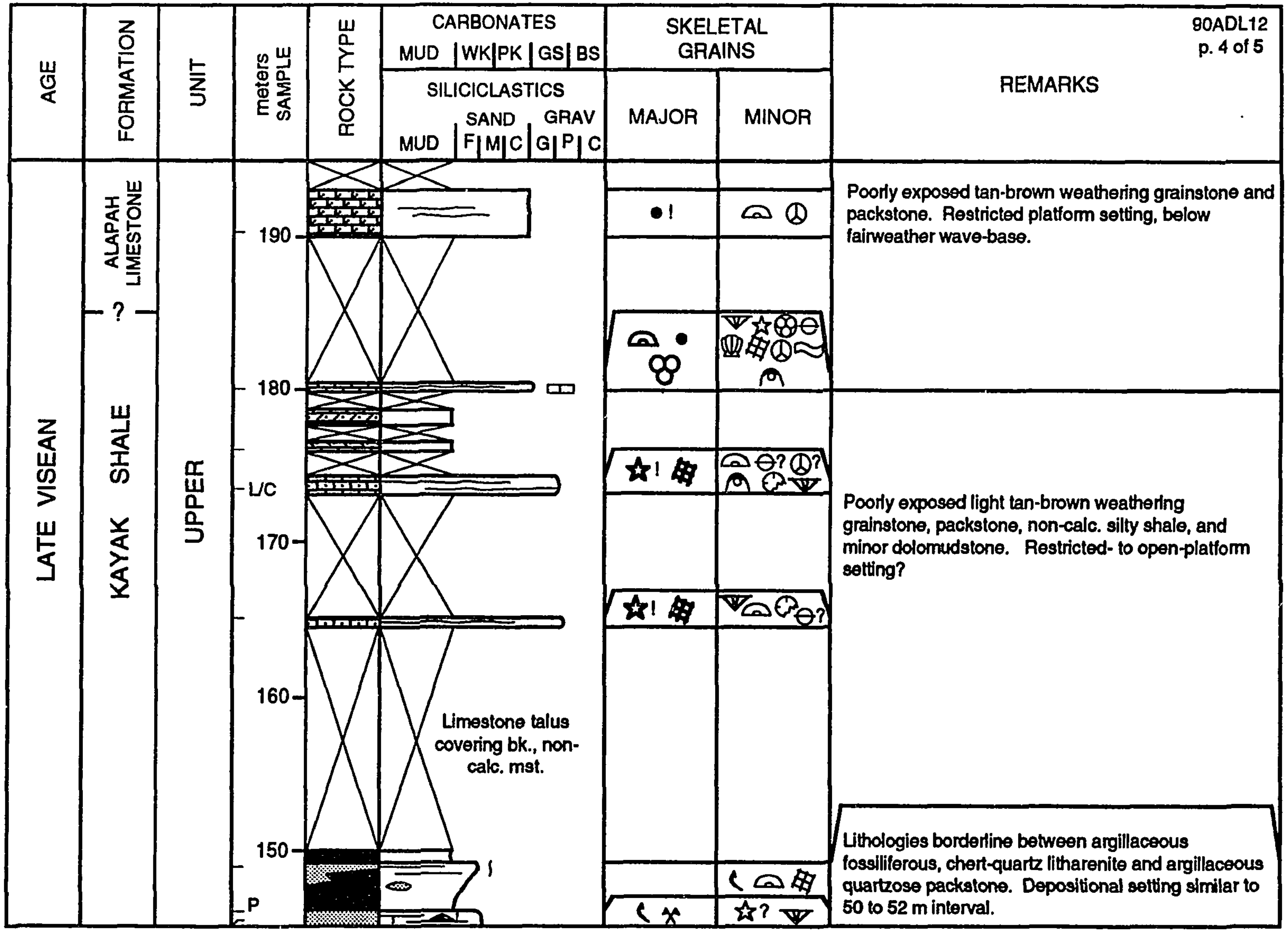
90ADL12
p. 2 of 5

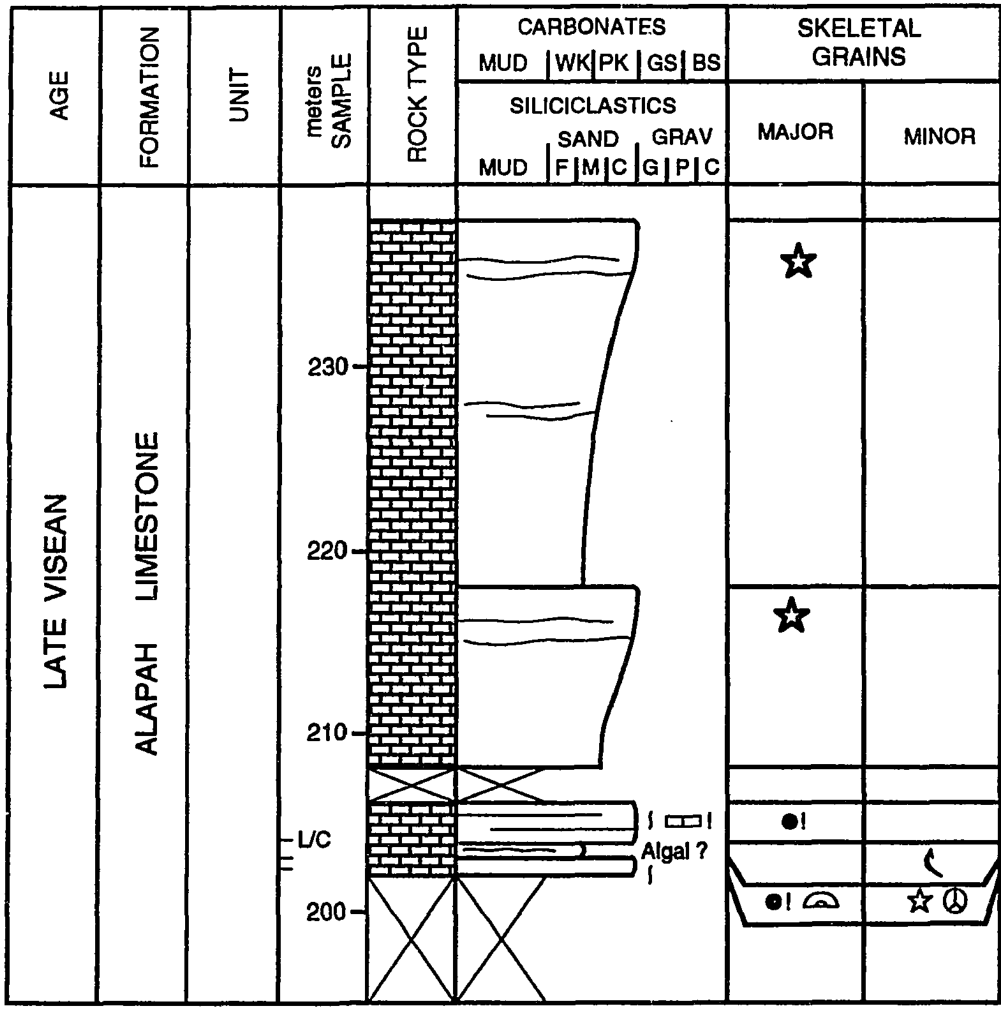
REMARKS

Black silty shale with minor interbeds of argillaceous sandstone and packstone.; leached pelmatozoan and brachiopod grains on parting surfaces. Depositional setting similar to 50 to 52 m interval.

Black to dark gray silty shale; interval capped by interbbed argillaceous packstone and sandstone beds; rare dark brown, isotropic grains in thin section- phosphate? Restricted- to marginally restricted (?)-platform setting, below fairweather wave-base. Black silty shale deposited below anaerobic to dysaerobic bottom water layer (restricted-platform). Sandstone and packstone deposited below marginally dysaerobic bottom water layer. Sandstone and packstone record shoaling-upward trend - shoaled above anaerobic bottom water layer. May record transport of sand and skeletal grains by storm-generated currents? Poorly exposed, geometry of sandstone and packstone beds is not known, so more detailed environmental interpretation is not possible.

AGE	FORMATION	UNIT	meters SAMPLE	ROCK TYPE	CARBONATES: MUD, WK, PK, GS, BS / SILICICLASTICS: MUD, SAND (F, M, C), GRAV (G, P, C)	SKELETAL GRAINS: MAJOR	SKELETAL GRAINS: MINOR	REMARKS
VISEAN	KAYAK SHALE	UPPER	140			! ?		Red-orange weathering, burrow-mottled, argillaceous, calc., fossiliferous, chert-quartz lithic wacke and litharenite, argillaceous quartzose packstone, and black non-calc. silty shale; possible detrital dolomite at 145 m. Depositional setting similar to 50 to 52 m interval.
		?	130, Float, 120					Talus cover; float consists of argillaceous spiculitic, chert-quartz litharenite and quartzose pelmatozoan-ostracod packstone.
		MIDDLE	110, 100					Black, non-calc. silty shale; common leached bivalve and pelmatozoan grains on parting surfaces. Deposited in restricted-platform setting, below fairweather wave-base and anaerobic to dysaerobic bottom water layer. Shelly fauna is sparse and allochthonous?

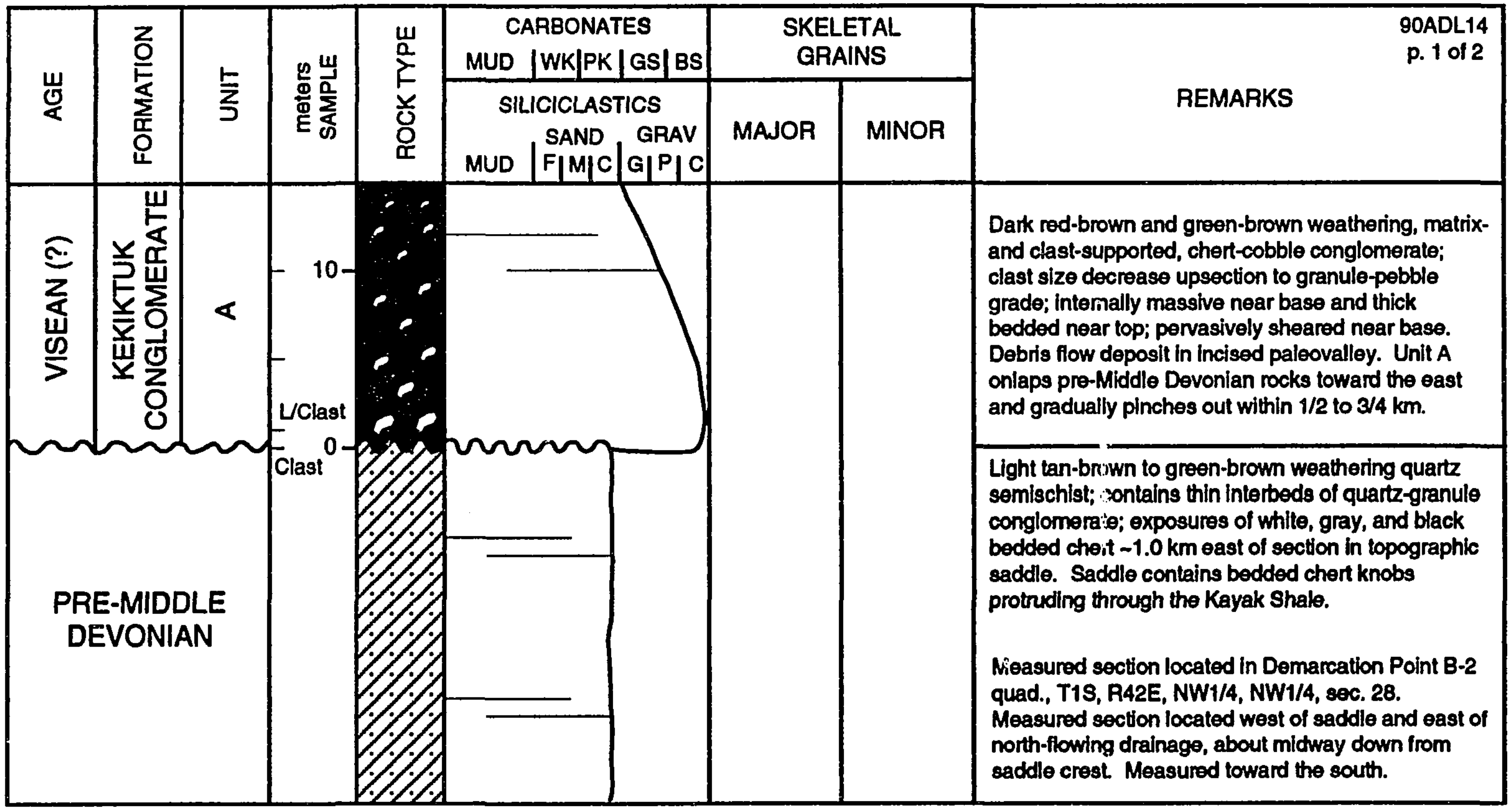

90ADL12
p. 4 of 5
AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD
WK
PK
GS
BS
SILICICLASTICS
SAND
GRAV
MUD
F
M
C
G
P
C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
LATE VISEAN
ALAPAH LIMESTONE
?
KAYAK SHALE
UPPER
190
180
L/C
170
160
150
P
Limestone talus covering bk., non-calc. mst.
Poorly exposed tan-brown weathering grainstone and packstone. Restricted platform setting, below fairweather wave-base.
Poorly exposed light tan-brown weathering grainstone, packstone, non-calc. silty shale, and minor dolomudstone. Restricted- to open-platform setting?
Lithologies borderline between argillaceous fossiliferous, chert-quartz litharenite and argillaceous quartzose packstone. Depositional setting similar to 50 to 52 m interval.



90ADL12
p. 5 of 5

REMARKS

Light gray weathering wackestone/packstone and possible lime mudstone.; fenestral fabric in packstone between 202-205 m. Restricted- to open-platform setting. Peloidal packstone and interbedded algal? lime mudstone probably record shallow-marine deposition in a restricted-platform setting with elevated salinity.


90ADL14
p. 1 of 2
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
MUD SAND F M C GRAV G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
VISEAN (?)
KEKIKTUK CONGLOMERATE
A
10
L/Clast
0
Clast
PRE-MIDDLE DEVONIAN
Dark red-brown and green-brown weathering, matrix- and clast-supported, chert-cobble conglomerate; clast size decrease upsection to granule-pebble grade; internally massive near base and thick bedded near top; pervasively sheared near base. Debris flow deposit in incised paleovalley. Unit A onlaps pre-Middle Devonian rocks toward the east and gradually pinches out within 1/2 to 3/4 km.
Light tan-brown to green-brown weathering quartz semischist; contains thin interbeds of quartz-granule conglomerate; exposures of white, gray, and black bedded chert ~1.0 km east of section in topographic saddle. Saddle contains bedded chert knobs protruding through the Kayak Shale.
Measured section located in Demarcation Point B-2 quad., T1S, R42E, NW1/4, NW1/4, sec. 28. Measured section located west of saddle and east of north-flowing drainage, about midway down from saddle crest. Measured toward the south.

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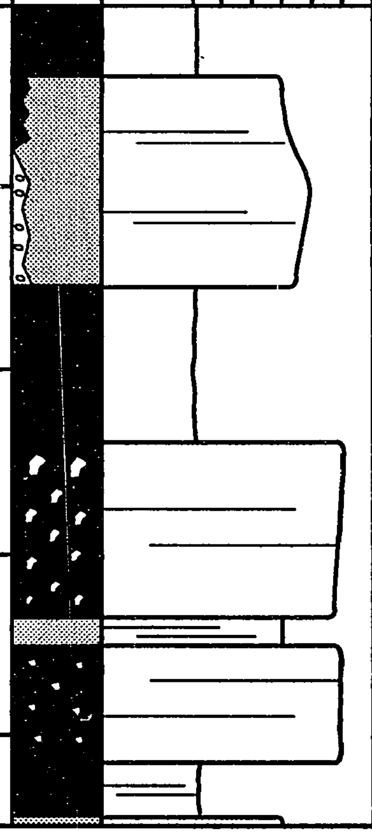
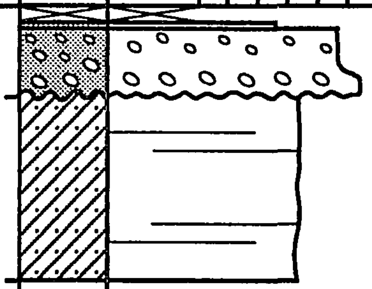
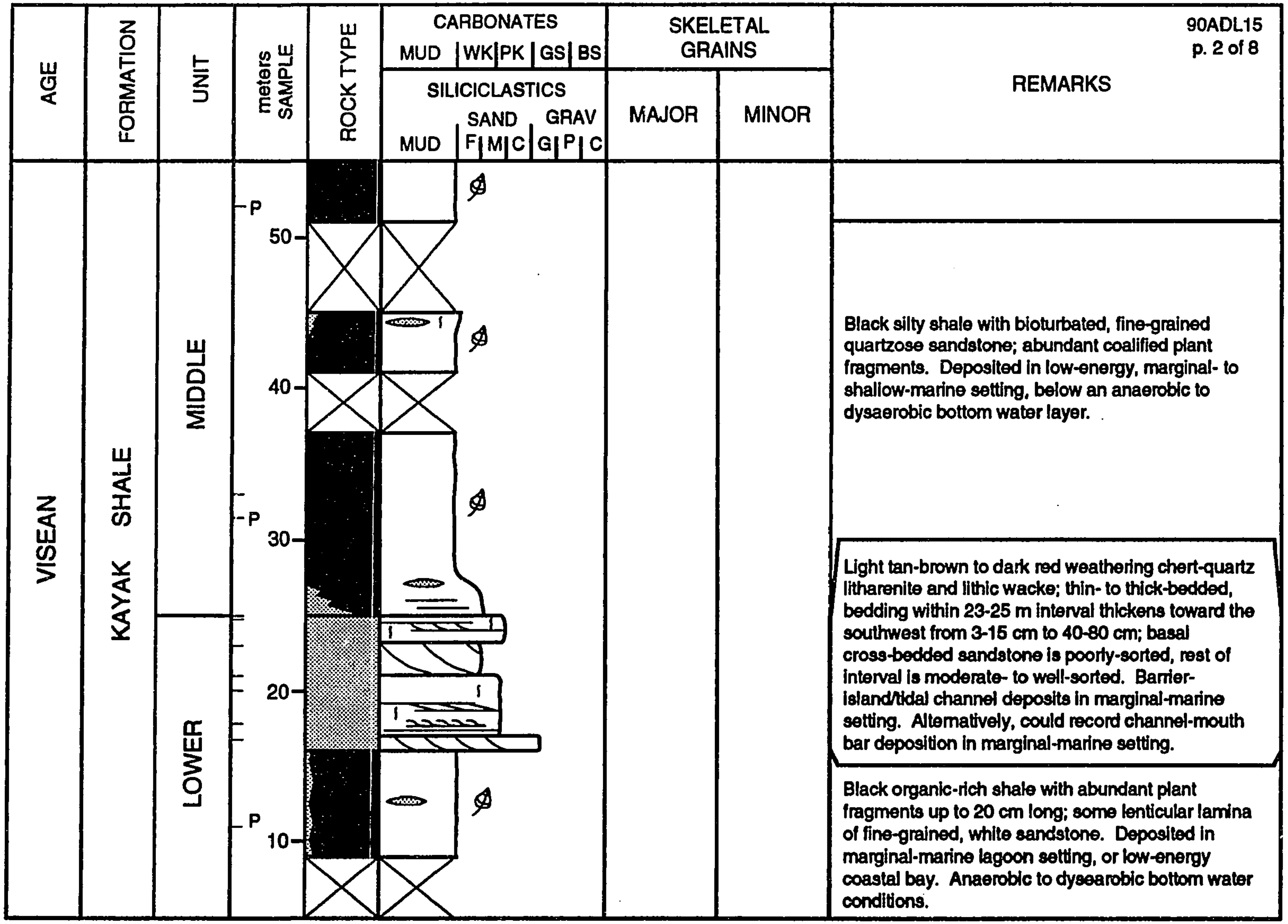
p. 2 of 2

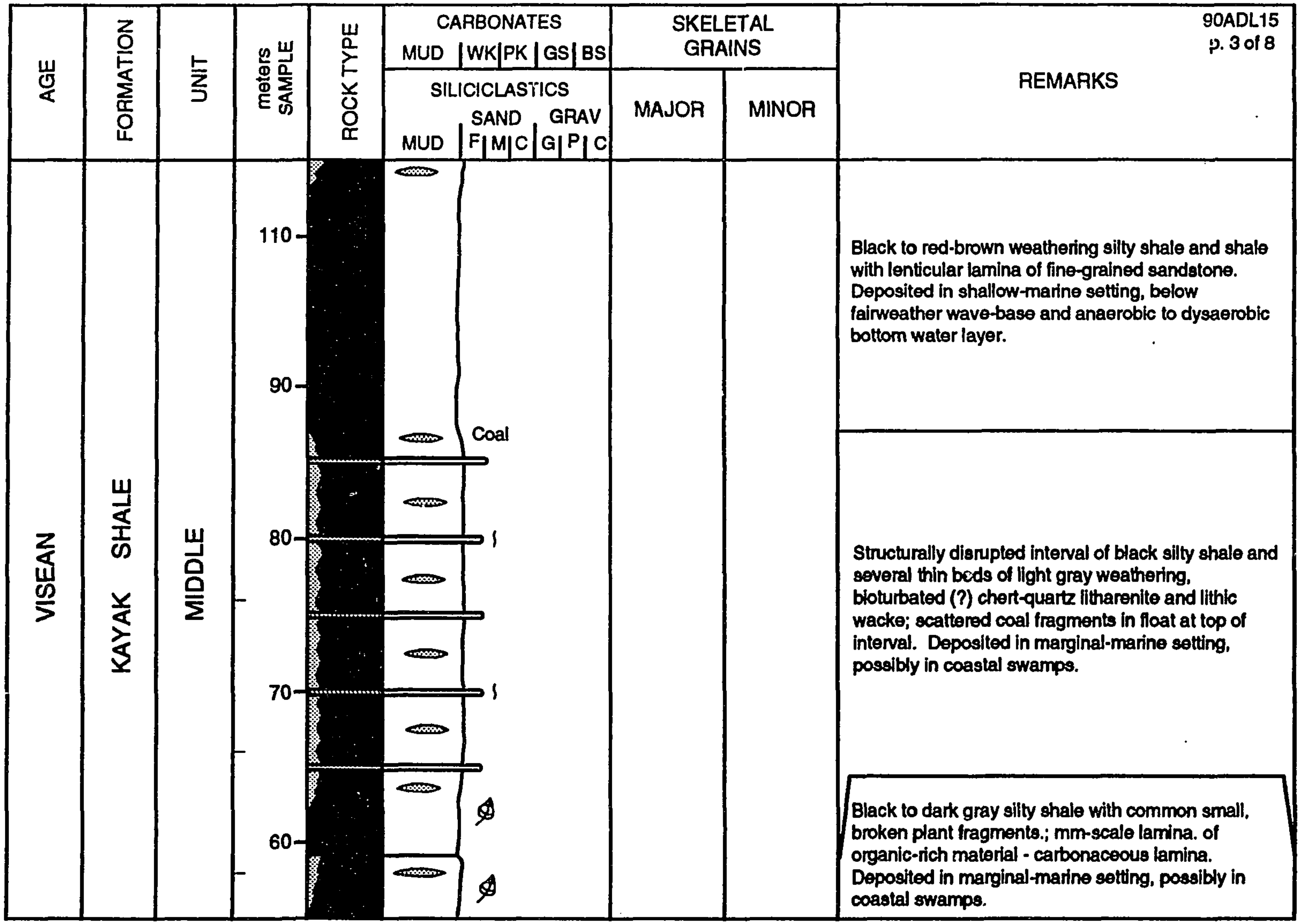
AGE	FORMATION	UNIT	meters SAMPLE	ROCK TYPE	CARBONATES: MUD, WK, PK, GS, BS / SILICICLASTICS: MUD, SAND (F, M, C), GRAV (G, P, C)	SKELETAL GRAINS: MAJOR	SKELETAL GRAINS: MINOR	REMARKS
VISEAN (?)	KAYAK SHALE	MIDDLE						Exposures of black silty shale continue toward south.
	KEKIKTUK CONGLOMERATE	E ?	50					Gray and red weathering, very coarse-grained chert litharenite and chert-granule conglomerate distinct salt & pepper look on fresh surface; parallel thin-to medium- bedded; some thin black silty shale partings; individual beds appear internally structuress; detrital grains are moderately sorted and moderately rounded. Reworked debris flow deposits in the lower foreshore/upper shoreface zone of a beach. Probably distal part of fan delta.
			P 40					Black mudstone; poorly exposed.
		A	30, 20					Dark gray and green-gray weathering matrix-supported chert-pebble conglomerate; angular clasts of white, gray, and black bedded chert from 4-15 cm; interbedded green-gray mudstone with granules and pebbles of chert floating in mudstone matrix; upper conglomerate body coarsens upward; matrix in conglomerate is chert lithic wacke/cherty msudstone; detrital grains are angular- to sub-angular and poorly-sorted to unsorted. Debris flow deposits in incised paleovalley. Probably part of small alluvial fan/fan delta.



AGE	FORMATION	UNIT	meters SAMPLE	ROCK TYPE	CARBONATES: MUD, WK, PK, GS, BS / SILICICLASTICS: MUD, SAND (F, M, C), GRAV (G, P, C)	SKELETAL GRAINS: MAJOR	SKELETAL GRAINS: MINOR	REMARKS (90ADL15 p. 1 of 8)
L. TOURN. (?) -VISEAN	KEKIKTUK CONGLOM.	A ?	0					Clast-supported, chert-quartz pebble conglomerate; clasts angular and range from 0.5 to 4 cm; matrix consists of coarse-grained sand- and granule-size grains; capped by snow-white quartzite with minor interbedded organic-rich mudstone. Deposited in fluvial setting. Poorly exposed - cannot be more specific.
PRE-MIDDLE DEVONIAN								Light tan-brown to green-brown weathering phyllitic quartzite with thin-beds (<405 cm) of granule conglomerate. Exposures of white, gray, and black bedded chert ~1.5 km east of section.
								Measured section located in Demarcation Point B-2 quad., T1S, R42E, E1/2, SE1/4, sec. 19. Measured toward the south, along the west bank of a north-flowing drainage. Whale Mountain volcanics have been thrust over the Lisburne Group and dominate the skyline south of the measured section.




90ADL15
p. 2 of 8
AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD | WK | PK | GS | BS
SILICICLASTICS
MUD
SAND
F M C
GRAV
G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
VISEAN
KAYAK SHALE
MIDDLE
LOWER
P
50
40
P
30
20
P
10
Black silty shale with bioturbated, fine-grained quartzose sandstone; abundant coalified plant fragments. Deposited in low-energy, marginal- to shallow-marine setting, below an anaerobic to dysaerobic bottom water layer.
Light tan-brown to dark red weathering chert-quartz litharenite and lithic wacke; thin- to thick-bedded, bedding within 23-25 m interval thickens toward the southwest from 3-15 cm to 40-80 cm; basal cross-bedded sandstone is poorly-sorted, rest of interval is moderate- to well-sorted. Barrier-island/tidal channel deposits in marginal-marine setting. Alternatively, could record channel-mouth bar deposition in marginal-marine setting.
Black organic-rich shale with abundant plant fragments up to 20 cm long; some lenticular lamina of fine-grained, white sandstone. Deposited in marginal-marine lagoon setting, or low-energy coastal bay. Anaerobic to dysaerobic bottom water conditions.


90ADL15
p. 3 of 8
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
MUD SAND F M C GRAV G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
VISEAN
KAYAK SHALE
MIDDLE
110
90
80
70
60
Coal
Black to red-brown weathering silty shale and shale with lenticular lamina of fine-grained sandstone. Deposited in shallow-marine setting, below fairweather wave-base and anaerobic to dysaerobic bottom water layer.
Structurally disrupted interval of black silty shale and several thin bcds of light gray weathering, bioturbated (?) chert-quartz litharenite and lithic wacke; scattered coal fragments in float at top of interval. Deposited in marginal-marine setting, possibly in coastal swamps.
Black to dark gray silty shale with common small, broken plant fragments.; mm-scale lamina. of organic-rich material - carbonaceous lamina. Deposited in marginal-marine setting, possibly in coastal swamps.

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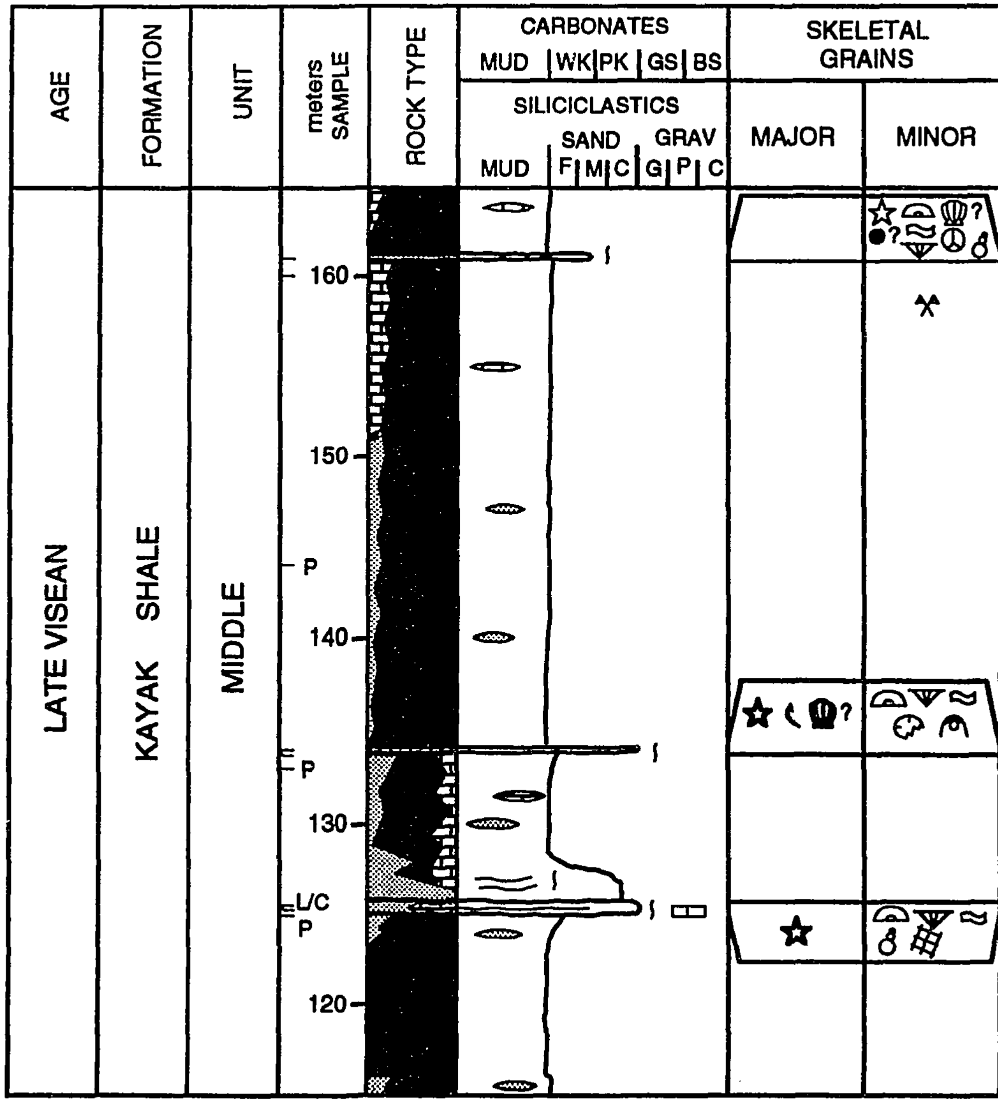
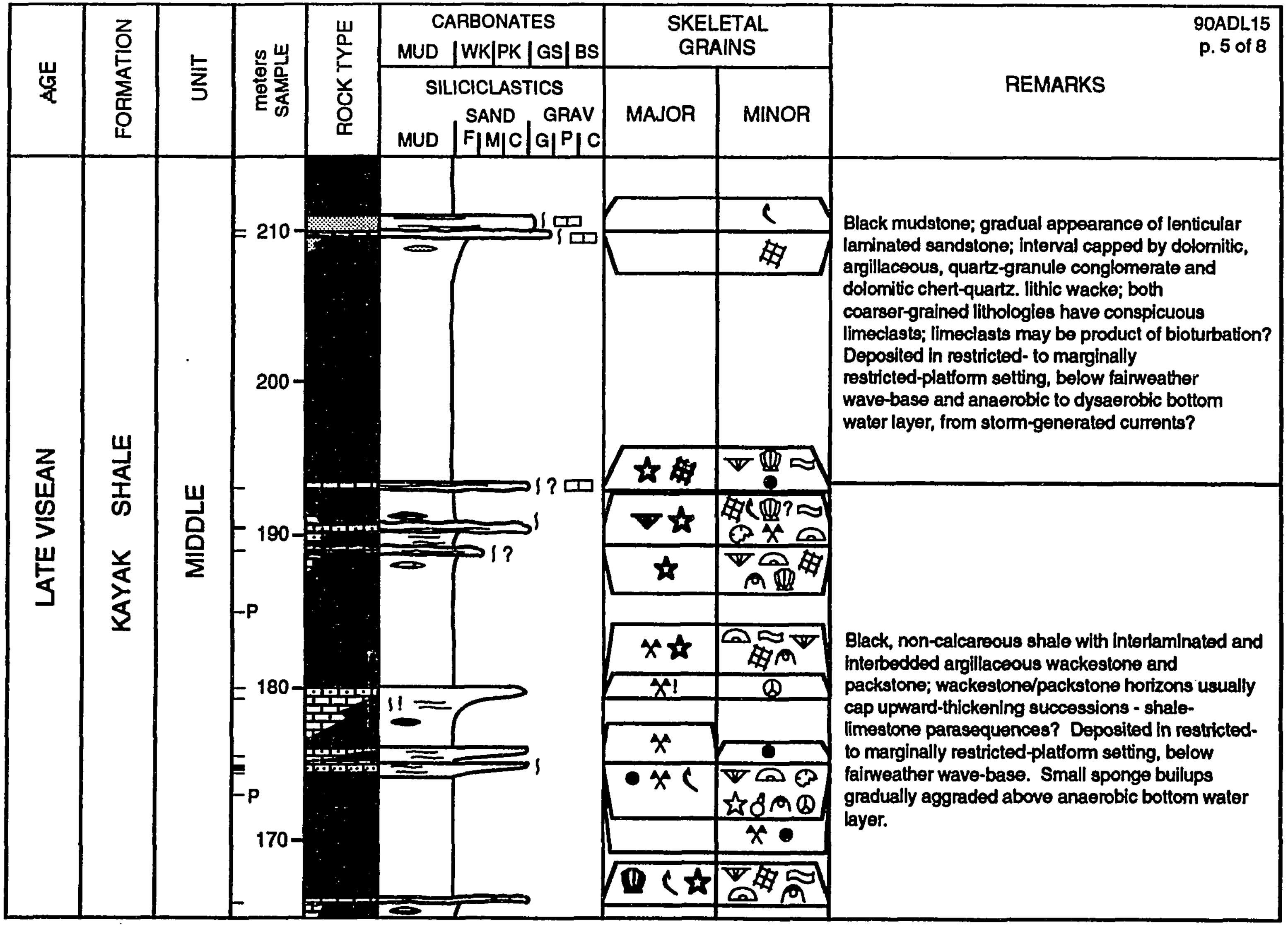
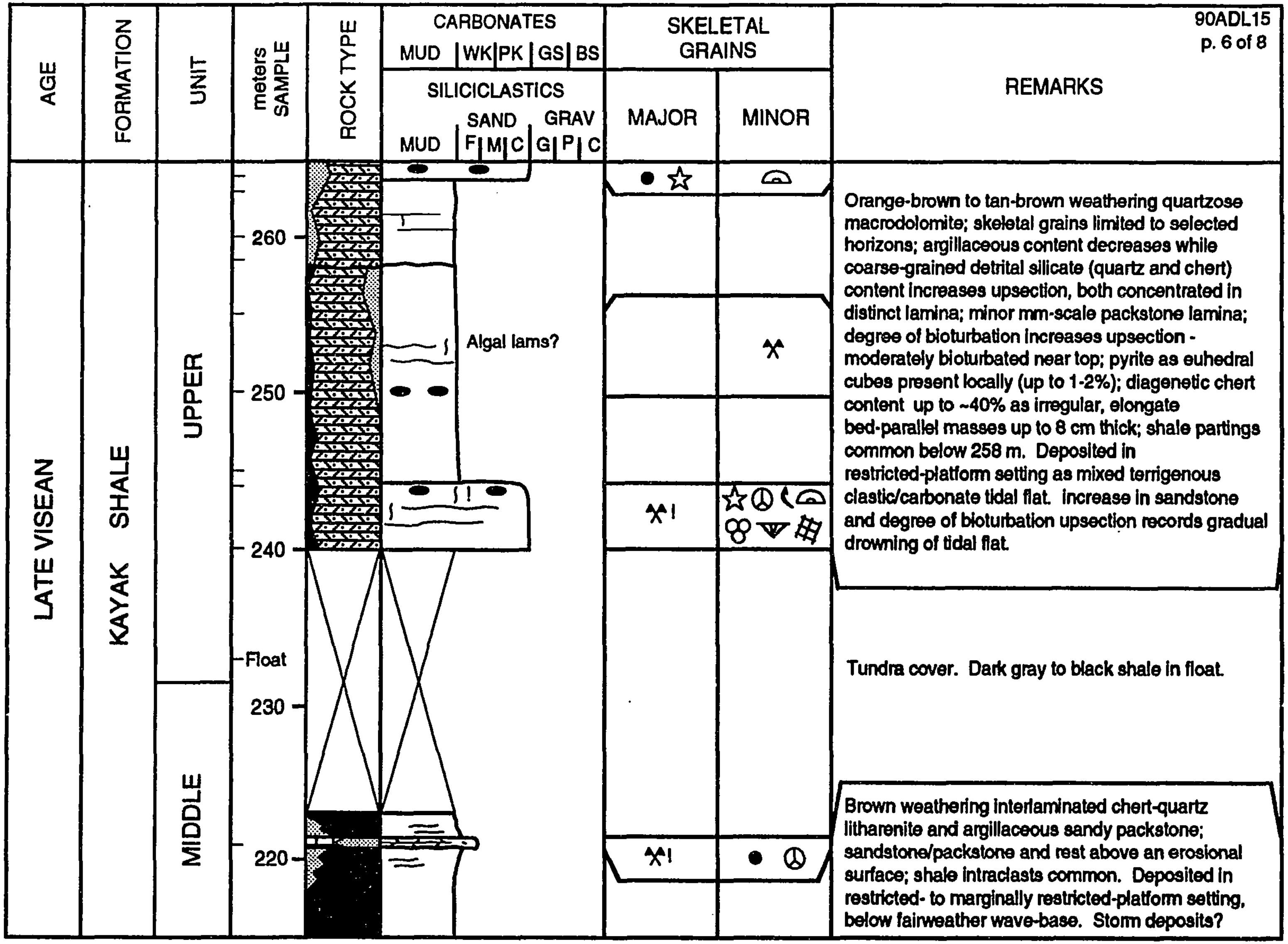
p. 4 of 8

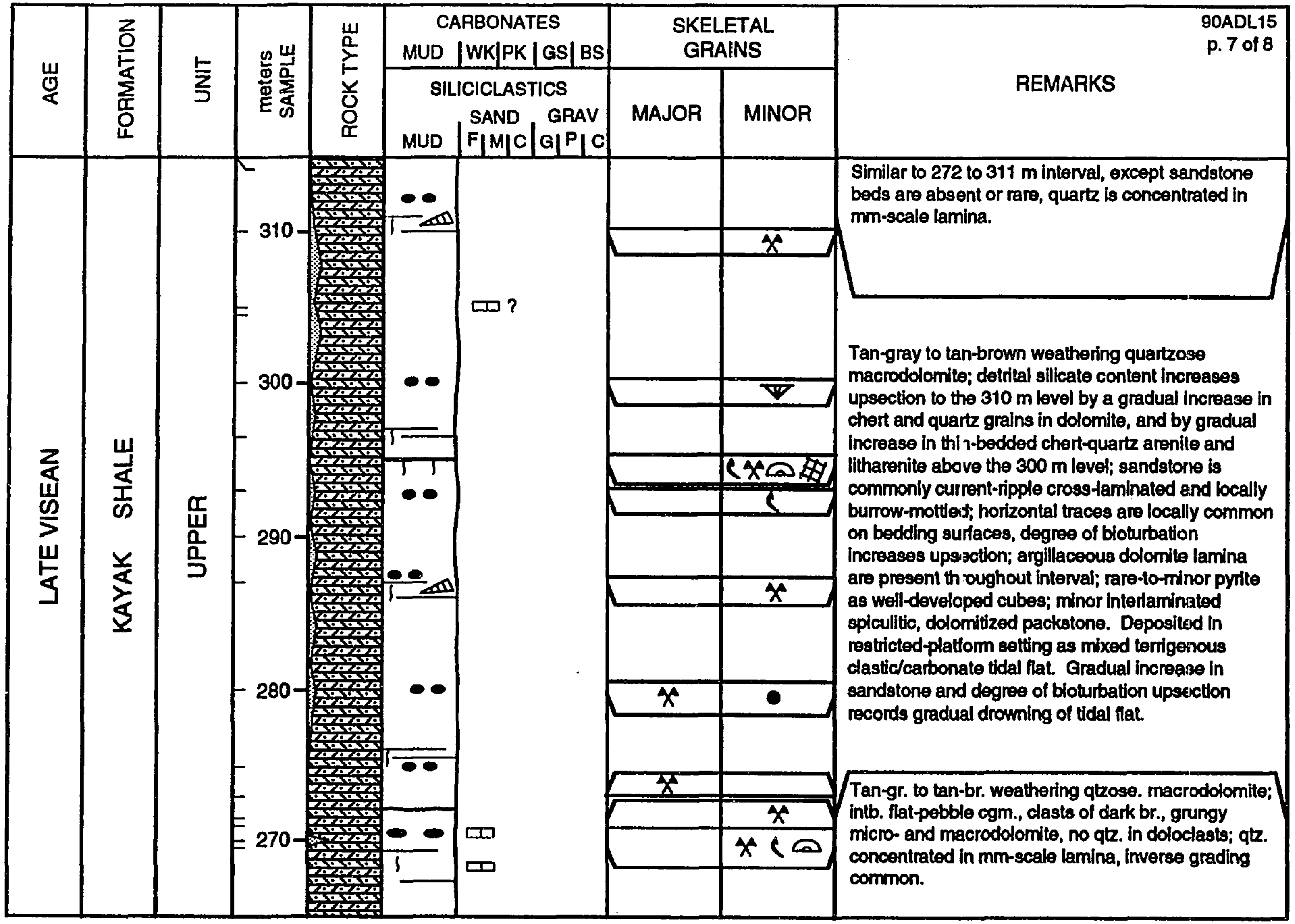


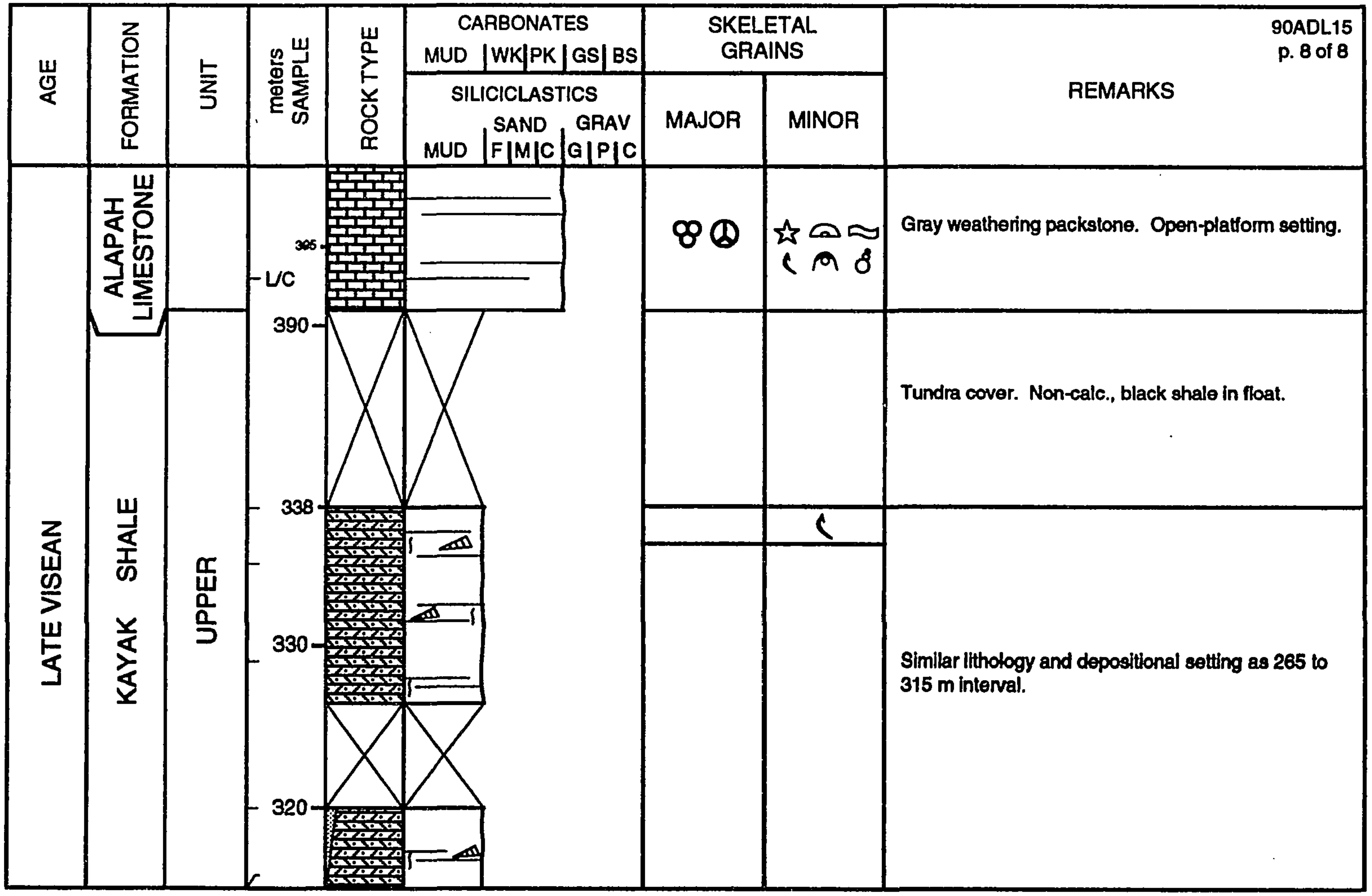
REMARKS

Black non-calc. silty shale with interlaminated quartzose sandstone, and minor wackestone and packstone. Deposited in shallow-marine setting, below fairweather wave-base and an anaerobic to dysaerobic bottom water layer. Most limestone beds have sharp, erosive (?) bases and broken and abraded skeletal grains, which suggest deposition from storm-generated currents. Skeletal grains were probably derived from more open-marine settings located farther offshore (south).


90ADL15
p. 5 of 8
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
LATE VISEAN
KAYAK SHALE
MIDDLE
210
200
190
180
170
P
P
Black mudstone; gradual appearance of lenticular laminated sandstone; interval capped by dolomitic, argillaceous, quartz-granule conglomerate and dolomitic chert-quartz. lithic wacke; both coarser-grained lithologies have conspicuous limeclasts; limeclasts may be product of bioturbation? Deposited in restricted- to marginally restricted-platform setting, below fairweather wave-base and anaerobic to dysaerobic bottom water layer, from storm-generated currents?
Black, non-calcareous shale with interlaminated and interbedded argillaceous wackestone and packstone; wackestone/packstone horizons usually cap upward-thickening successions - shale-limestone parasequences? Deposited in restricted- to marginally restricted-platform setting, below fairweather wave-base. Small sponge builups gradually aggraded above anaerobic bottom water layer.


90ADL15
p. 6 of 8
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
LATE VISEAN
KAYAK SHALE
UPPER
MIDDLE
260
250
240
Float
230
220
Algal lams?
Orange-brown to tan-brown weathering quartzose macrodolomite; skeletal grains limited to selected horizons; argillaceous content decreases while coarse-grained detrital silicate (quartz and chert) content increases upsection, both concentrated in distinct lamina; minor mm-scale packstone lamina; degree of bioturbation increases upsection - moderately bioturbated near top; pyrite as euhedral cubes present locally (up to 1-2%); diagenetic chert content up to ~40% as irregular, elongate bed-parallel masses up to 8 cm thick; shale partings common below 258 m. Deposited in restricted-platform setting as mixed terrigenous clastic/carbonate tidal flat. Increase in sandstone and degree of bioturbation upsection records gradual drowning of tidal flat.
Tundra cover. Dark gray to black shale in float.
Brown weathering interlaminated chert-quartz litharenite and argillaceous sandy packstone; sandstone/packstone and rest above an erosional surface; shale intraclasts common. Deposited in restricted- to marginally restricted-platform setting, below fairweather wave-base. Storm deposits?


90ADL15
p. 7 of 8
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
LATE VISEAN
KAYAK SHALE
UPPER
310
300
290
280
270
?
Similar to 272 to 311 m interval, except sandstone beds are absent or rare, quartz is concentrated in mm-scale lamina.
Tan-gray to tan-brown weathering quartzose macrodolomite; detrital silicate content increases upsection to the 310 m level by a gradual increase in chert and quartz grains in dolomite, and by gradual increase in thin-bedded chert-quartz arenite and litharenite above the 300 m level; sandstone is commonly current-ripple cross-laminated and locally burrow-mottled; horizontal traces are locally common on bedding surfaces, degree of bioturbation increases upsection; argillaceous dolomite lamina are present throughout interval; rare-to-minor pyrite as well-developed cubes; minor interlaminated spiculitic, dolomitized packstone. Deposited in restricted-platform setting as mixed terrigenous clastic/carbonate tidal flat. Gradual increase in sandstone and degree of bioturbation upsection records gradual drowning of tidal flat.
Tan-gr. to tan-br. weathering qtzose. macrodolomite; intb. flat-pebble cgm., clasts of dark br., grungy micro- and macrodolomite, no qtz. in doloclasts; qtz. concentrated in mm-scale lamina, inverse grading common.



AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD | WK | PK | GS | BS
SILICICLASTICS
SAND GRAV
MUD | F | M | C | G | P | C
SKELETAL GRAINS
MAJOR
MINOR
REMARKS
90ADL15
p. 8 of 8
LATE VISEAN
ALAPAH LIMESTONE
KAYAK SHALE
UPPER
395
L/C
390
338
330
320
Gray weathering packstone. Open-platform setting.
Tundra cover. Non-calc., black shale in float.
Similar lithology and depositional setting as 265 to 315 m interval.

1991 MEASURED SECTION KEY

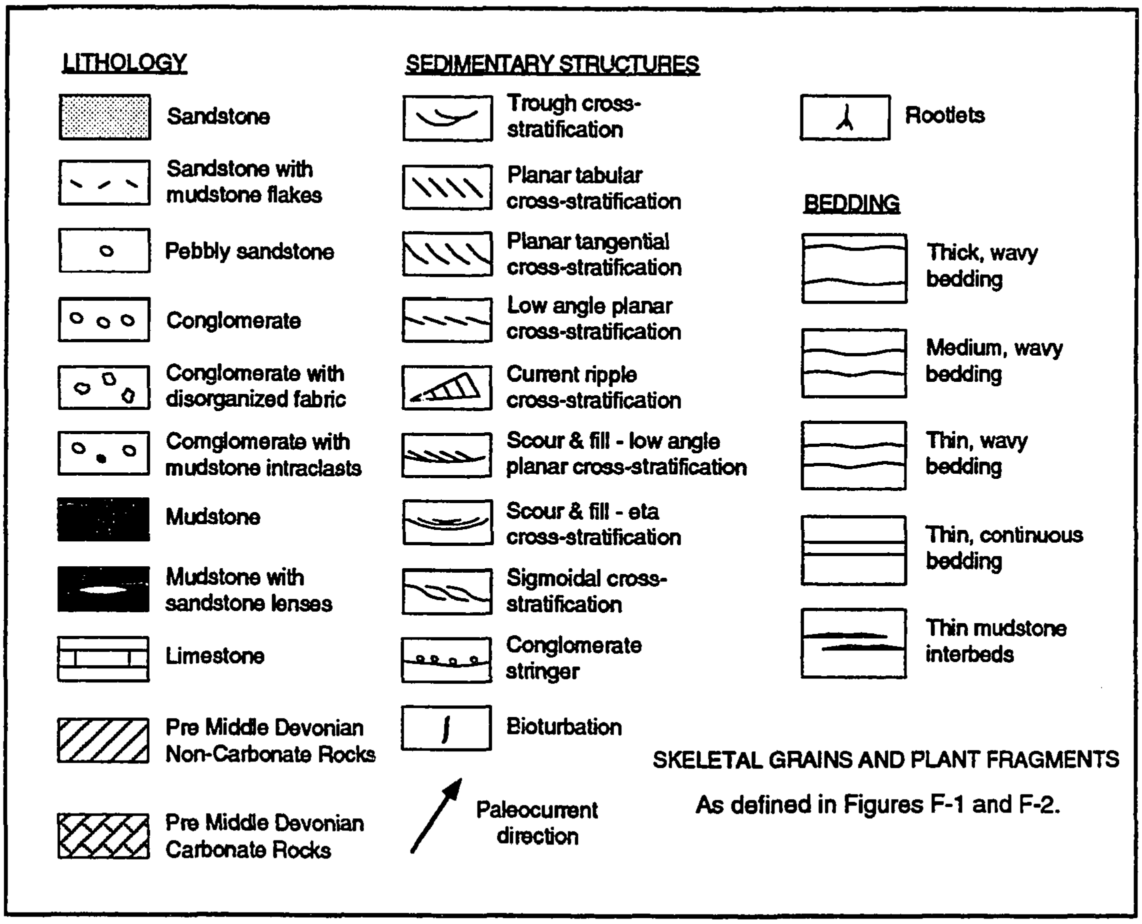
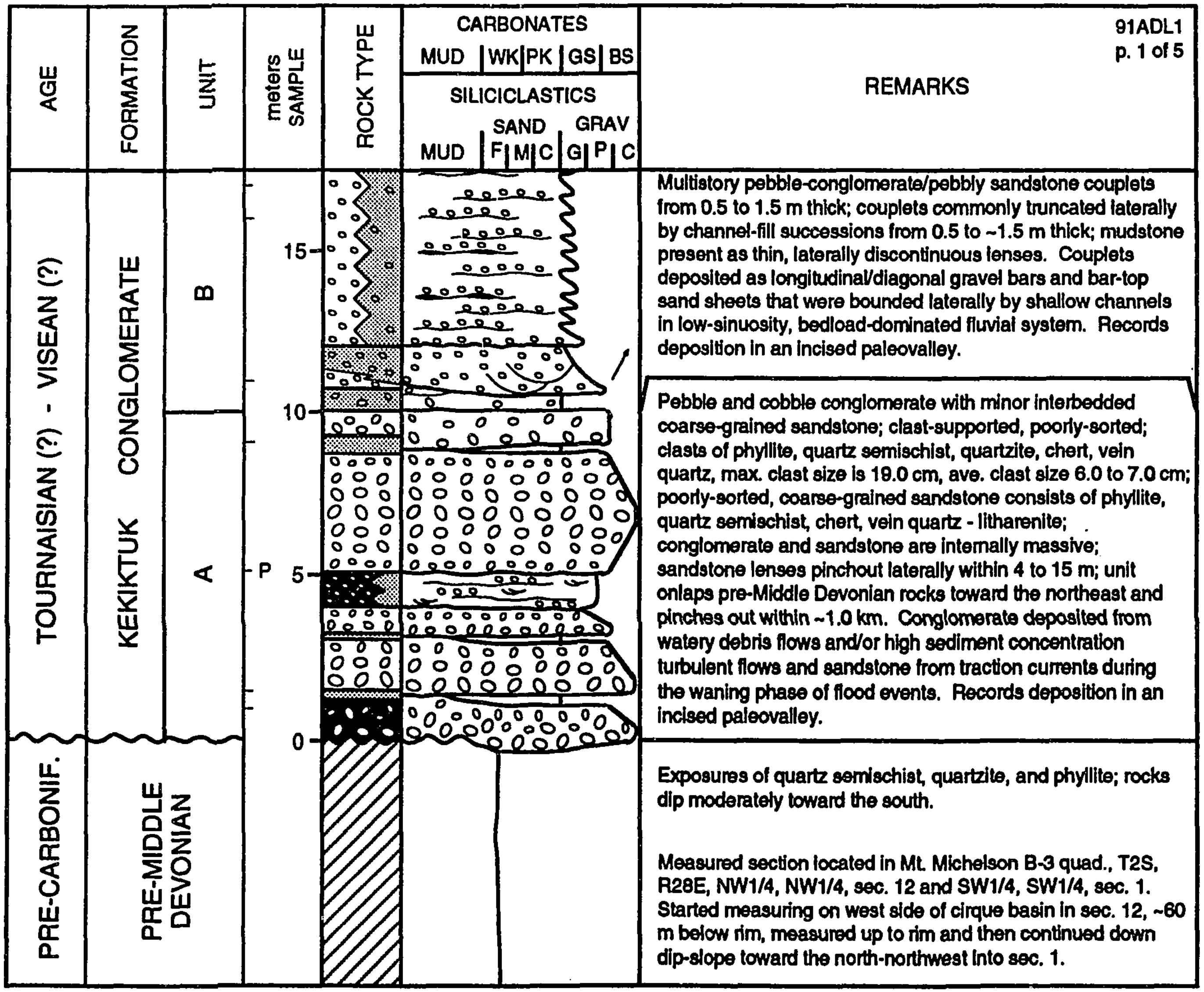


Figure F-3 - Symbols used in measured sections obtained during the 1991 field season. Some symbols defined previously in Figures F-1 and F-2.


91ADL1
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AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
MUD SAND F M C GRAV G P C
REMARKS
TOURNAISIAN (?) - VISEAN (?)
KEKIKTUK CONGLOMERATE
B
A
P
15
10
5
0
Multistory pebble-conglomerate/pebbly sandstone couplets from 0.5 to 1.5 m thick; couplets commonly truncated laterally by channel-fill successions from 0.5 to ~1.5 m thick; mudstone present as thin, laterally discontinuous lenses. Couplets deposited as longitudinal/diagonal gravel bars and bar-top sand sheets that were bounded laterally by shallow channels in low-sinuosity, bedload-dominated fluvial system. Records deposition in an incised paleovalley.
Pebble and cobble conglomerate with minor interbedded coarse-grained sandstone; clast-supported, poorly-sorted; clasts of phyllite, quartz semischist, quartzite, chert, vein quartz, max. clast size is 19.0 cm, ave. clast size 6.0 to 7.0 cm; poorly-sorted, coarse-grained sandstone consists of phyllite, quartz semischist, chert, vein quartz - litharenite; conglomerate and sandstone are internally massive; sandstone lenses pinchout laterally within 4 to 15 m; unit onlaps pre-Middle Devonian rocks toward the northeast and pinches out within ~1.0 km. Conglomerate deposited from watery debris flows and/or high sediment concentration turbulent flows and sandstone from traction currents during the waning phase of flood events. Records deposition in an incised paleovalley.
PRE-CARBONIF.
PRE-MIDDLE DEVONIAN
Exposures of quartz semischist, quartzite, and phyllite; rocks dip moderately toward the south.
Measured section located in Mt. Michelson B-3 quad., T2S, R28E, NW1/4, NW1/4, sec. 12 and SW1/4, SW1/4, sec. 1. Started measuring on west side of cirque basin in sec. 12, ~60 m below rim, measured up to rim and then continued down dip-slope toward the north-northwest into sec. 1.

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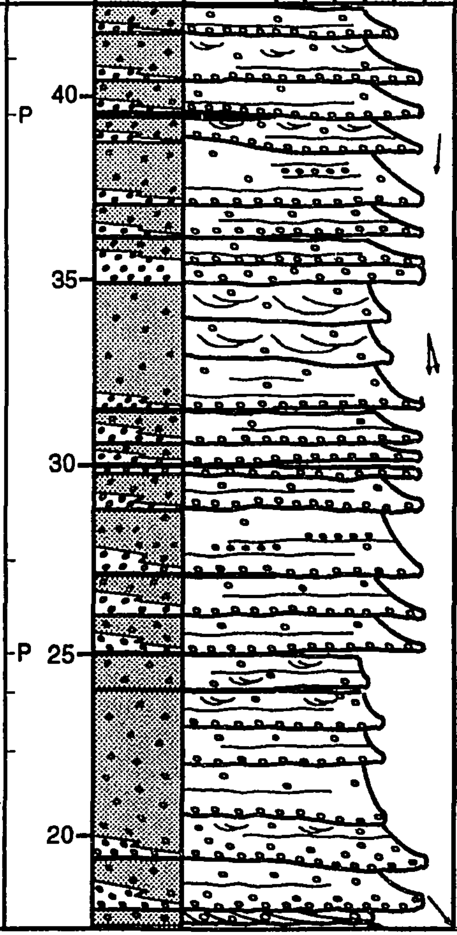
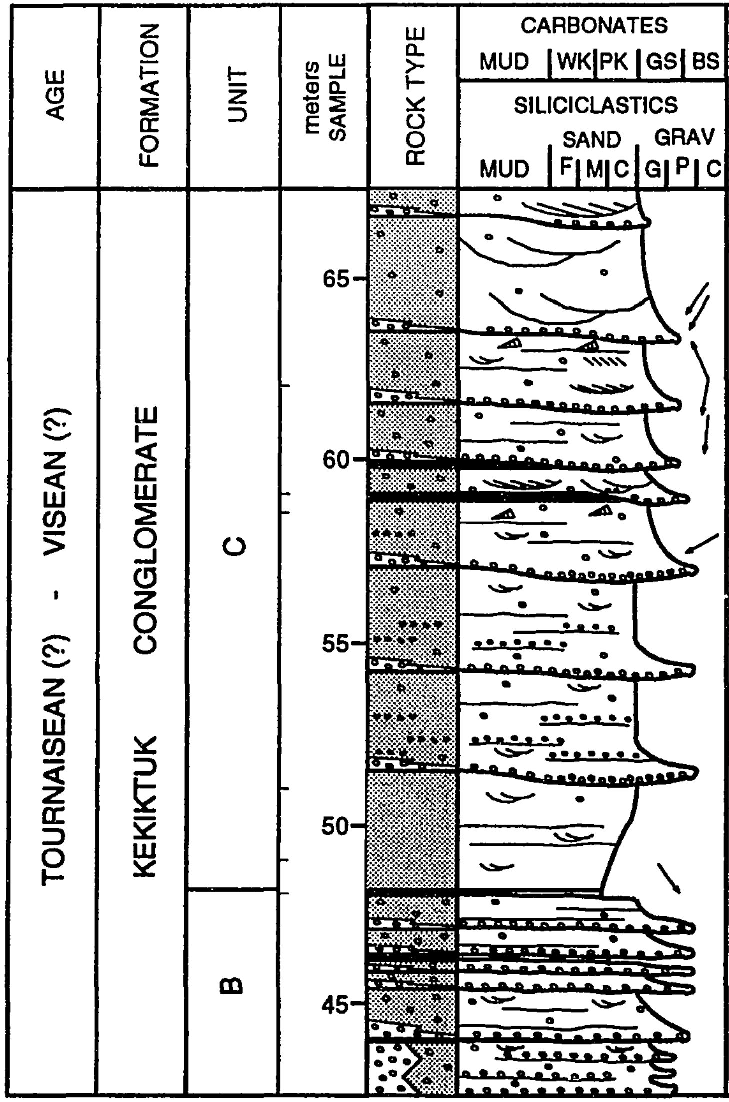
p. 2 of 5

AGE	FORMATION	UNIT	meters SAMPLE	ROCK TYPE	CARBONATES: MUD, WK, PK, GS, BS / SILICICLASTICS: MUD, SAND (F, M, C), GRAV (G, P, C)	REMARKS
TOURNAISEAN (?) - VISEAN (?)	KEKIKTUK CONGLOMERATE	B				15 - 48 m Pebble conglomerate and coarse-grained sandstone; clast-supported, disorganized clast fabric-to poorly-developed imbricate fabric, chert and vein quartz pebble conglomerate, matrix of tightly-packed, poorly-sorted, coarse-grained litharenite-to-sublitharenite; interbedded pebbly, poor-to moderately-sorted, coarse-grained chert-quartz sublitharenite; conglomerate and sandstone form fining-upward couplets characterized by erosional bases and gradual and abrupt transitions from conglomerate to sandstone; couplets commonly grade laterally into thin channel-fill successions; sandstones may be internally massive, horizontally bedded, or trough cross-stratified. Couplets deposited as longitudinal/ diagonal bars that were bounded laterally by shallow channels in a bedload-dominated, low-sinuosity, fluvial system situated in an incised paleovalley.





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REMARKS

48 - 87 m
Pebbly coarse-grained sandstone and pebble conglomerate; moderately-sorted, sublitharenite, scattered clasts of gray and black chert and vein quartz; imbricated, clast-supported pebble conglomerate, clasts of quartzite, chert, and vein quartz, max clast size 6.4 cm, ave. clast size ~ 2.0 to 3.0 cm; interval consists of numerous fining upward channel-fill cycles (multistory) beginning with conglomeratic lag and passing abruptly into overlying trough and planar-cross stratified, medium-to thick-bedded pebbly sandstone, common low-relief scours filled with low-angle planar and eta cross-stratification, common discontinuous pebble stringers 1 to 2 clasts thick, complete channel margins rarely preserved; minor interbedded, organic-rich mudstone with locally abundant plant fragments and minor log impressions. Deposited in bedload-dominated, low-to moderate-sinuosity fluvial system; average channel depth greater than in unit B. Unit records deposition in the distal region of an incised paleovalley.

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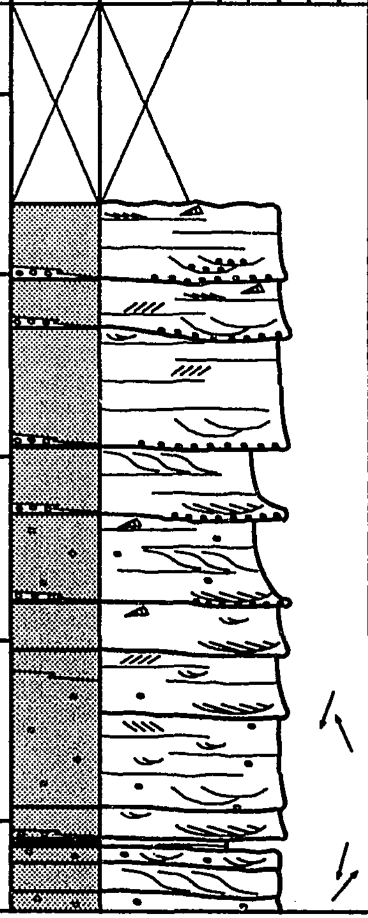
p. 4 of 5

AGE	FORMATION	UNIT	meters SAMPLE	ROCK TYPE	CARBONATES: MUD, WK, PK, GS, BS / SILICICLASTICS: MUD, SAND (F, M, C), GRAV (G, P, C)	REMARKS
TOURNAISEAN (?) - VISEAN (?)	KEKIKTUK CONGLOMERATE	C	90, 85, 80 (P), 75, 70			87 m - top ledge of cirque basin; dip slope descends toward the northwest to small, north-flowing drainage with small remnant of glacier in headwall area - pick up exposures of Kekiktuk Conglomereate on west side of this drainage. Thickness down dip slope and across drainage is uncertain. Total thickness of Kekiktuk in this section is conservative. Records deposition in low- to moderate-sinuosity, bedload-dominated fluvial system in incised paleovalley.

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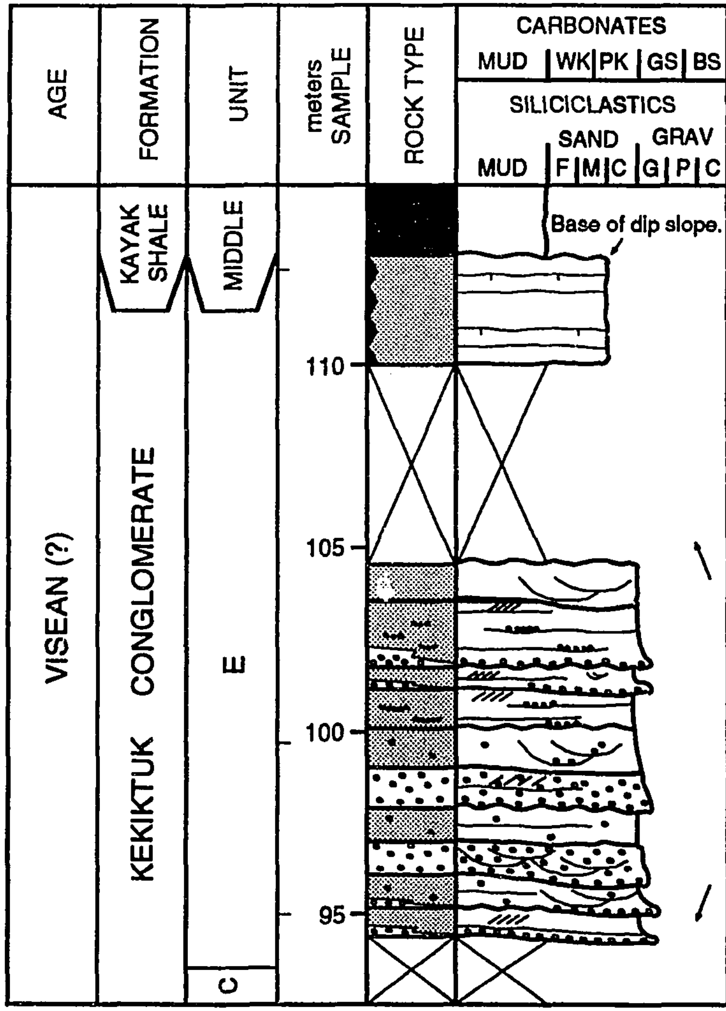
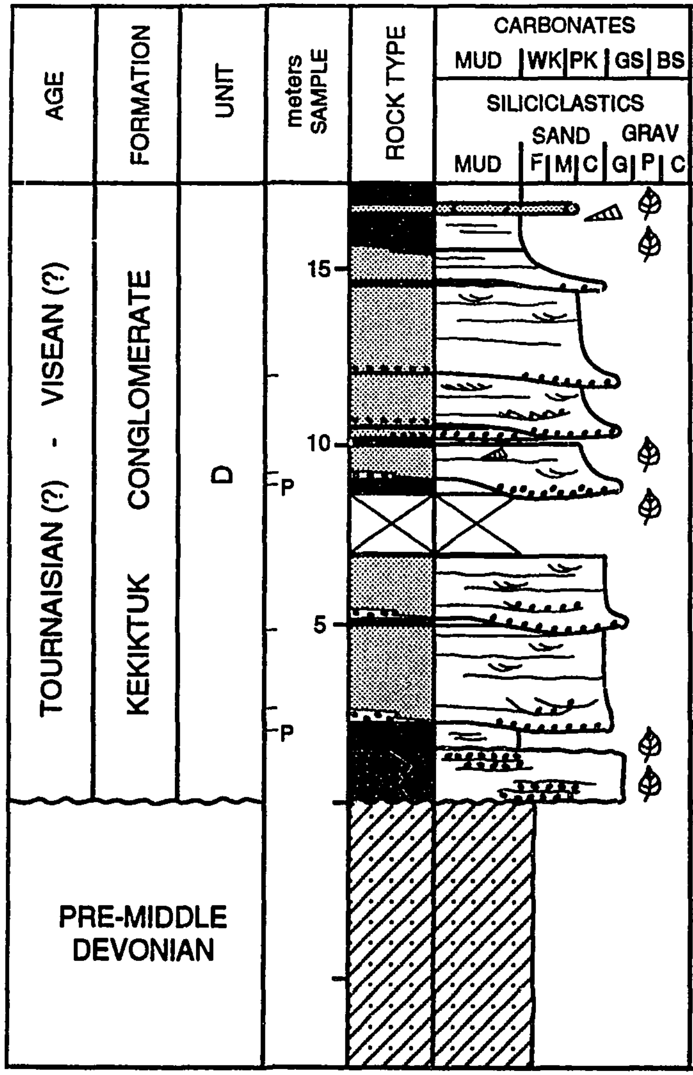
p. 5 of 5



REMARKS

Dark gray to black siltstone and silty shale with minor sharp-based sandstone beds (centimeter- to decimeter-scale) and bedsets (up to 3 m thick). Deposited in low-energy marginal- to shallow-marine setting. Water depth? Sandstone records frontal splays from fluvial flood events.

94 - 113 m
Pebbly sandstone and pebble conglomerate; pebbly, moderate-to well-sorted, chert and quartz sublitharenite and quaartzarenite, pebbles of chert and vein quartz; clast-supported, quartzite, chert, and vein quartz pebble conglomerate, quartzite decreases upsection; interval consists of numerous fining-upward channel-fills (multistory), each beginning with a conglomeratic lag overlying an irregular erosion surface and passing abruptly into overlying medium-bedded, pebbly sandstone; sandstones have variety of sedimentary structures including trough and planar cross-stratification, common low-relief scours filled with low-angle planar and *eta* cross-stratified sandstone; near top of unit, uppermost bed in channel-fills often contain megaripples (possible antidunes ?); highest beds in some channel-fills near top of unit contain even, nonparallel bedding commonly with low-angle, inclined laminae; minor interbedded mudstone with locally abundant plant fragments and minor log impressions. Deposited in a bedload-dominated, low-to moderate (?)-sinuosity fluvial system in the distal region of an incised paleovalley/alluvial plain and in a wave-influenced coastal setting as distributary mouth-bar and beach deposits. Marginal-marine rocks near top of unit probably record deposition in a non-barred estuary (e.g. Dalrymple et al., 1992).



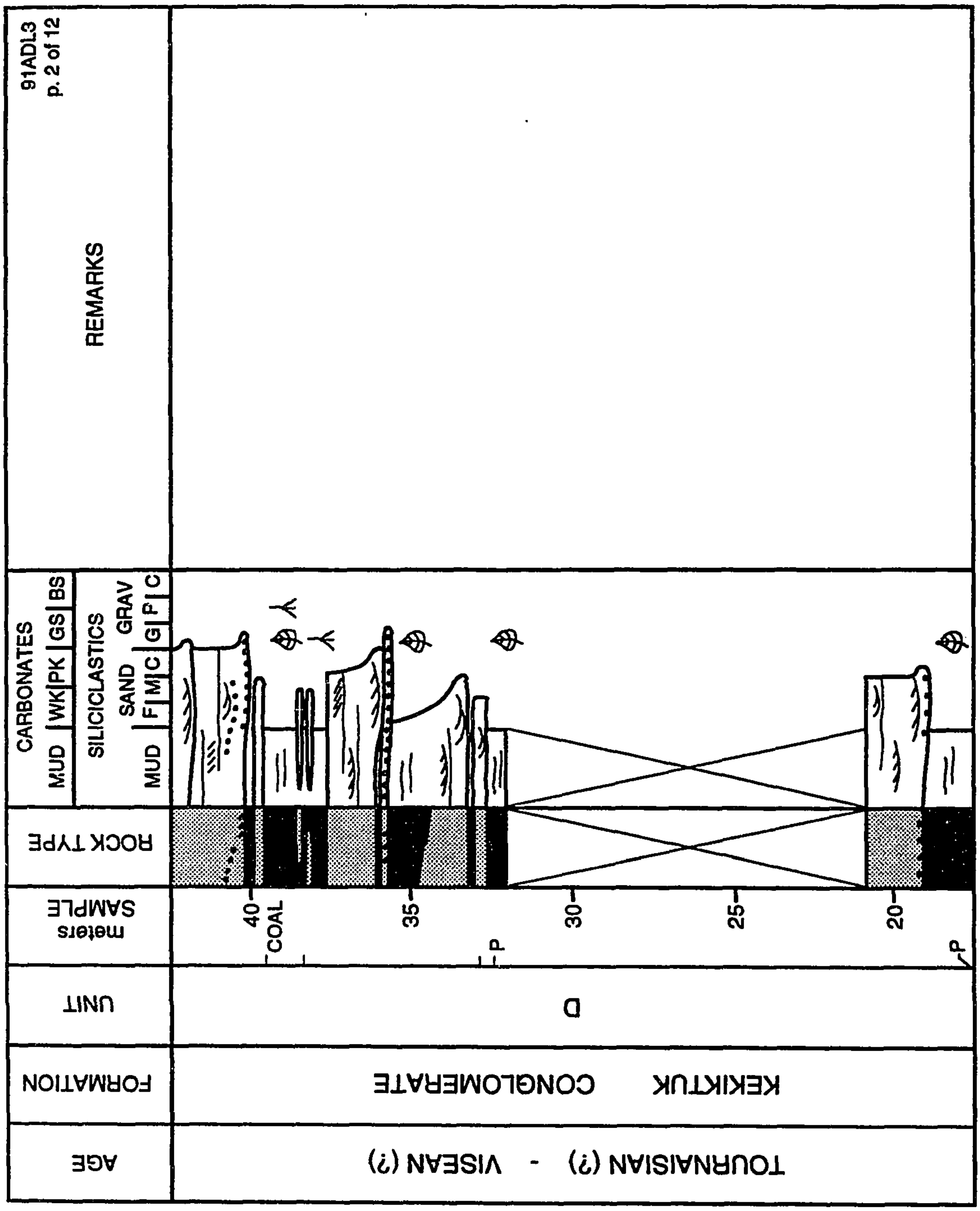
91ADL3
p. 1 of 12

REMARKS

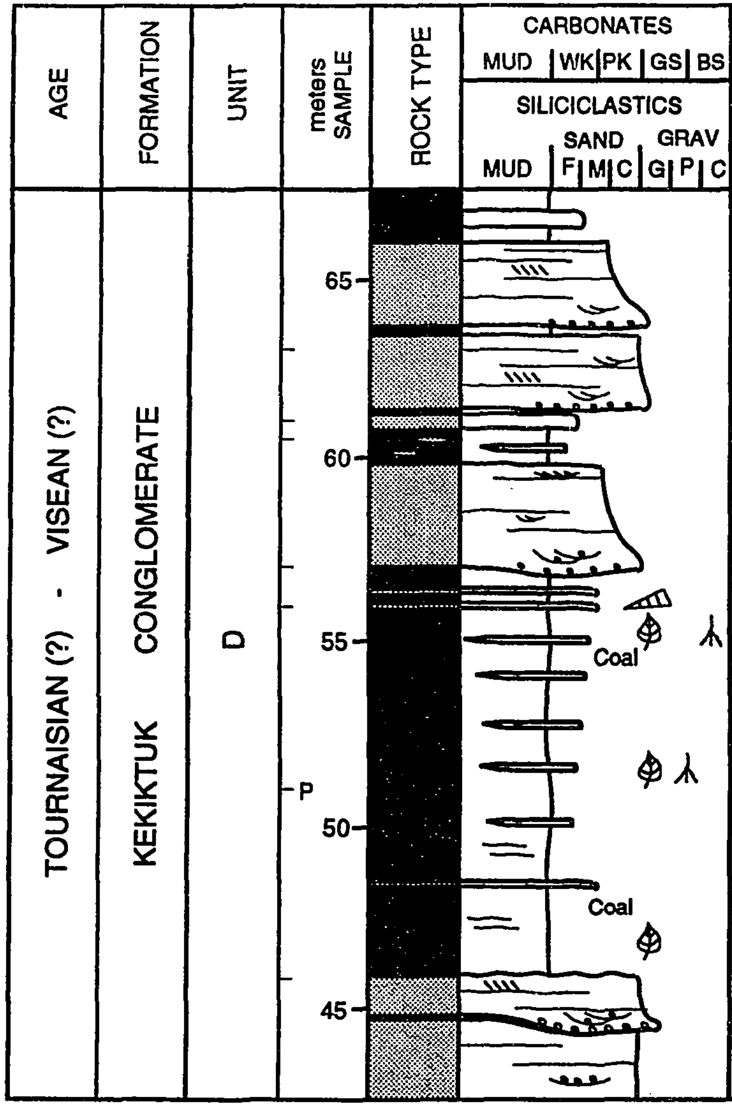
Poorly exposed, dark gray- to red-brown weathering sandy/granule-bearing mudstone, lithic wacke, or muddy conglomerate. Debris flow deposits ?

Poorly exposed green and red weathering phyllite and red-brown weathering sandstone.

Section located in Mt. Michelson B-3 quad., T2S, R27E, SW1/4, NE1/4, sec. 2, measured toward the north starting on the north side of small east-flowing tributary to Straight Creek. Continued down north-sloping dip slope and up steep south-facing slope, into the southern-most part of T1S, R27E, SW1/4, SE1/4, sec. 35.

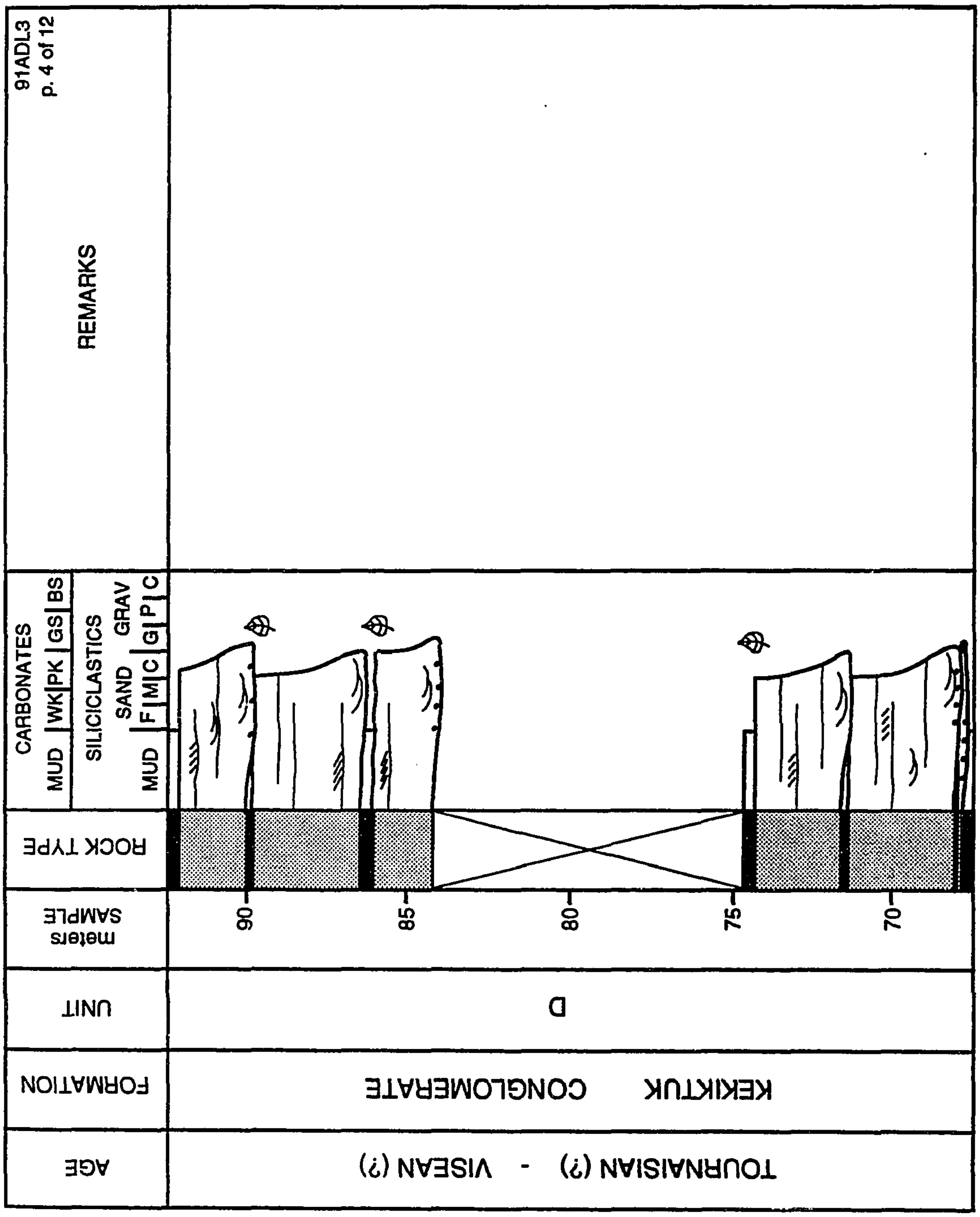

91ADL3
p. 2 of 12
REMARKS
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
MUD
SAND F M C
GRAV G F C
ROCK TYPE
meters
SAMPLE
40
COAL
35
P
30
25
20
P
UNIT
D
FORMATION
KEKIKTUK CONGLOMERATE
AGE
TOURNAISIAN (?) - VISEAN (?)

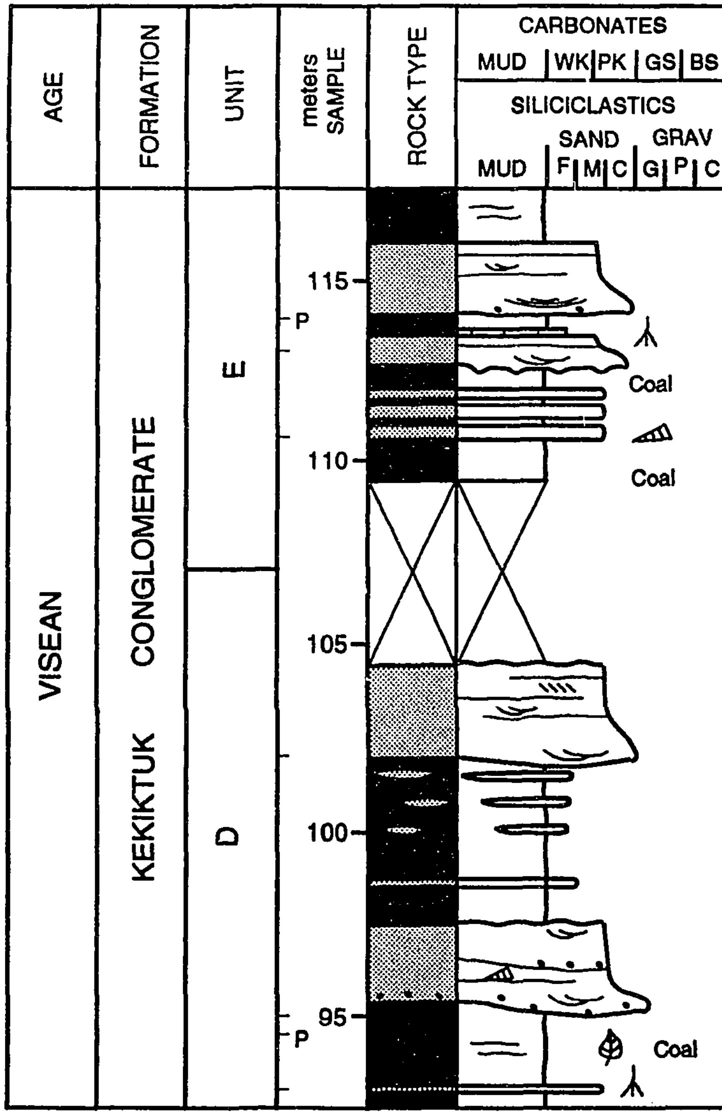
91ADL3
p. 3 of 12



REMARKS

2 - 104 m
Unit D consists of single and multistory fining upward cycles, each beginning with pebble conglomerate lag or coarse-grained pebbly sandstone that passes abruptly or gradationally into overlying medium- to coarse-grained, medium- to thick- bedded sandstone, top of completely preserved cycles consist of fine- to medium-grained sandstone and mudstone, cycles range from 1.0--10 m thick; sandstones contain variety of structures including trough and rare planar cross-stratification, horizontal stratification, and low-relief scour surfaces filled with low-angle planar and trough cross-stratification, bed surfaces near top of some cycles have straight-crested current ripples; mudstone intervals from 0.2 to 11m thick separate individual fining-upward cycles and groups of cycles and usually contain sharp-based sandstone beds, sandstone beds and mudstones commonly have bioturbate and/or rootlet structures. Deposited in mixed-load, moderate-to high-sinuosity fluvial system characterized by perennial floodbasins that occupied a broad, low-gradient, moderate-to-heavily vegetated, incised paleo valley.


91ADL3
p. 4 of 12
REMARKS
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
MUD
SAND
F M C
GRAV
G P C
ROCK TYPE
meters
SAMPLE
90
85
80
75
70
UNIT
D
FORMATION
KEKIKTUK CONGLOMERATE
AGE
TOURNAISIAN (?) - VISEAN (?)



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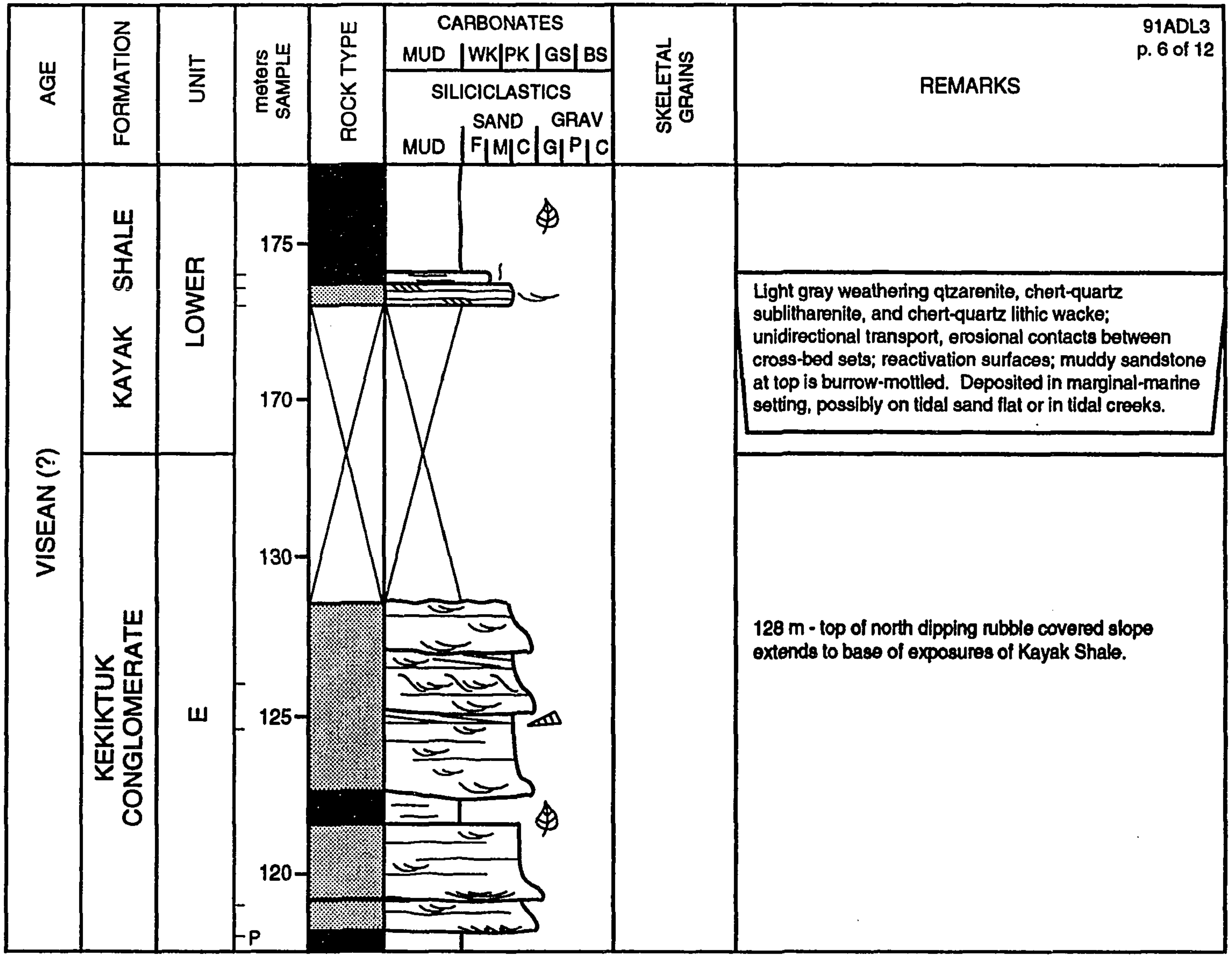
REMARKS

107 - 128 m
Sandstone, minor pebble conglomerate, and organic-rich mudstone; moderate-to well-sorted, chert and quartz sublitharenite and quartzarenite, locally occurring pebbles of chert and vein quartz; clast-supported chert, and vein quartz pebble conglomerate; interval consists of single and multistory fining-upward channel-fills, each beginning with a conglomeratic lag or coarse-grained sandstone above an erosion surface cut into sandstone or mudstone of the next lower cycle and pass abruptly into overlying medium-bedded sandstone; sandstones have variety of sedimentary structures including trough and planar cross-stratification, common low-relief scours filled with low-angle planar and eta cross-stratified sandstone; highest beds in channel-fills near top of unit contain planar, nonparallel bedding commonly with low-angle, inclined laminae; mudstone intervals separate individual channel-fills and amalgamated channel-fills, and contain abundant plant fragments and minor log impressions, base of some channel-fills have well-developed load structures (pillow-like structures) that protrude into underlying mudstone. Deposited in a bedload-dominated, moderate- to high-sinuosity fluvial system with associated small (?), perennial (?) floodbasins in the distal region of an incised paleovalley. Low-angle inclined lamina near the top of channel-fills at the top oft this interval record deposition as channel-mouth bar and/or adjacent beaches.



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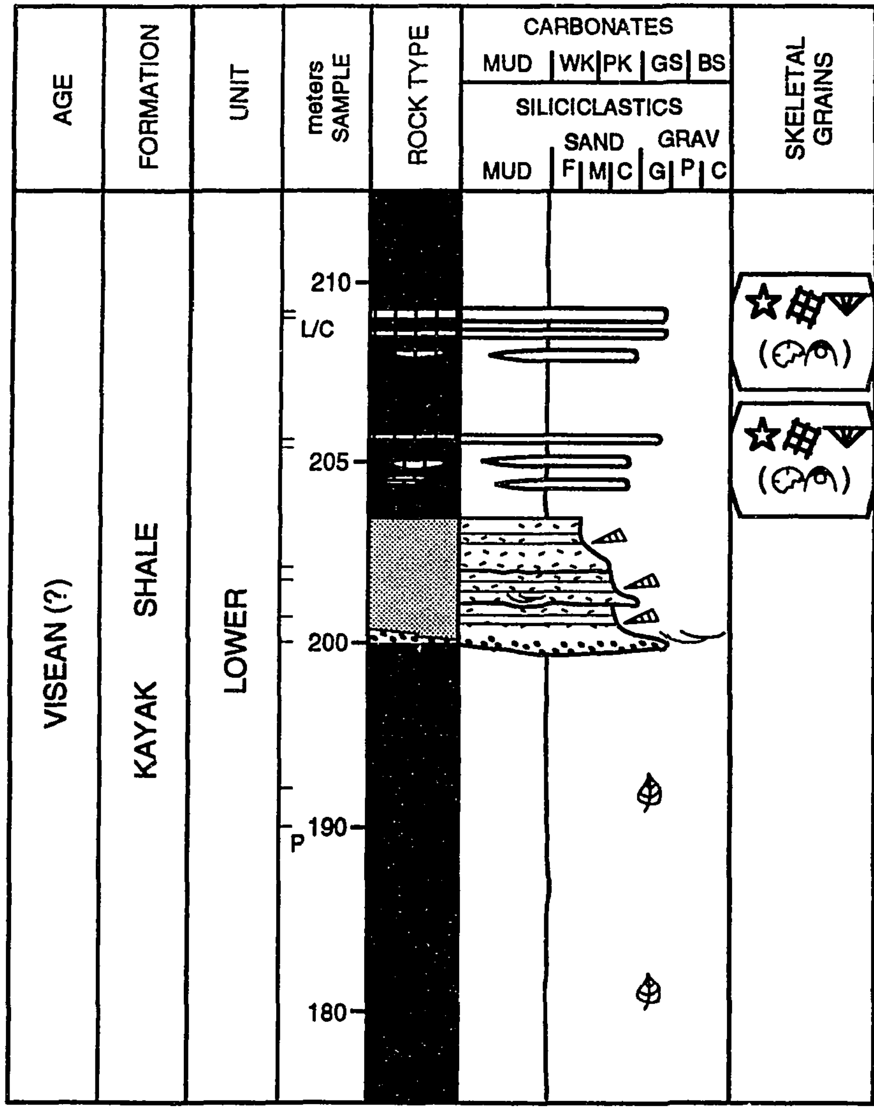
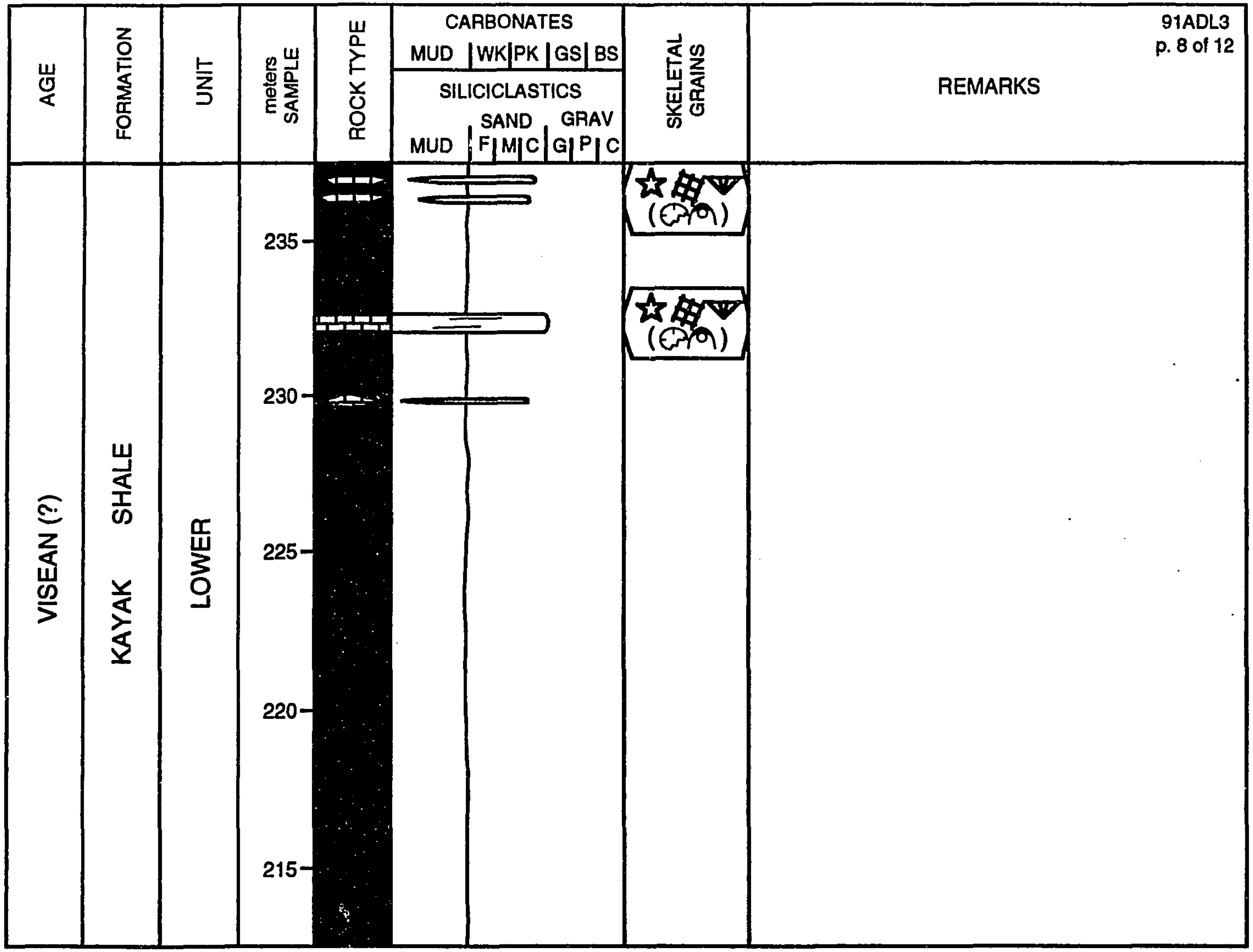
AGE
FORMATION
UNIT
meters SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
REMARKS
VISEAN (?)
KAYAK SHALE
LOWER
KEKIKTUK CONGLOMERATE
E
175
170
130
125
120
P
Light gray weathering qtzarenite, chert-quartz sublitharenite, and chert-quartz lithic wacke; unidirectional transport, erosional contacts between cross-bed sets; reactivation surfaces; muddy sandstone at top is burrow-mottled. Deposited in marginal-marine setting, possibly on tidal sand flat or in tidal creeks.
128 m - top of north dipping rubble covered slope extends to base of exposures of Kayak Shale.



REMARKS

128 - 237.5 m
Black siltstone, silty shale, argillaceous sandstone, and minor quartzose, bryozoan-pelmatozoan packstone/grainstone; siltstone and silty shale is dark gray-to-black; mudstone is commonly internally laminated with alternating siltstone and shale laminae; 3.5 to 4.0 m thick fining-upward succession at 200 m level, consists of argillaceous sandstone, erosive base, abundant mudstone chips up to 2.0 cm long; interlaminated and interbedded packstone/grainstone as sharp-based beds from <1.0 cm to over 15 cm thick, skeletal grains broken and abraded and arranged sub-parallel to bedding, common mudstone flakes also arranged sub-parallel to bedding, occur as individual beds of bedsets with individual beds separated by thin shale partings, lenticular geometry, lenses extending from <30 m to over 200 m along local strike; minor anthracitic coal near base of assemblage.
Deposited in back-barrier lagoon setting characterized by low-energy conditions with episodic influxes of skeletal material and minor terrigenous clastic sediment as overwash deposits associated with infrequent, major storms. Dark gray to black shale and siltstone suggests anaerobic to dysaerobic bottom water conditions. Normal marine fauna suggests derivation from open-platform settings located seaward of barrier-island (sand body at 237.5 m).
Sand body at 200 m interpreted as amalgamated frontal splay deposits that resulted from at least two, possibly three, separate fluvial flood events.



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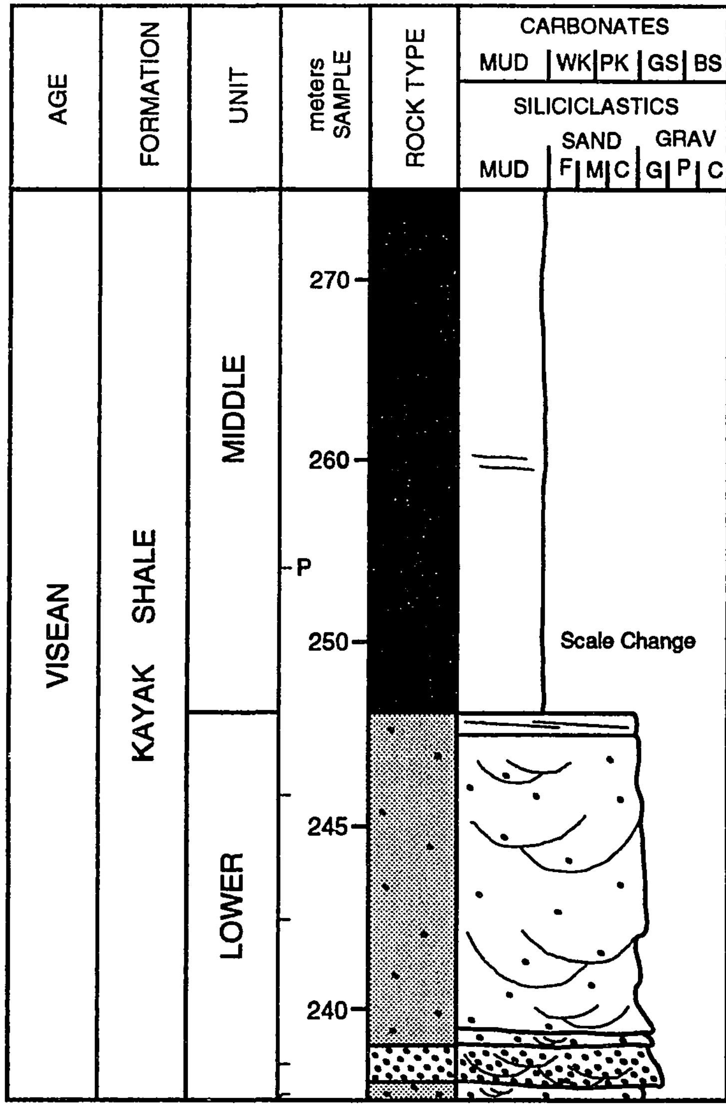
AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD
WK
PK
GS
BS
SILICICLASTICS
MUD
SAND
F
M
C
GRAV
G
P
C
SKELETAL GRAINS
REMARKS
VISEAN (?)
KAYAK SHALE
LOWER
235
230
225
220
215



REMARKS

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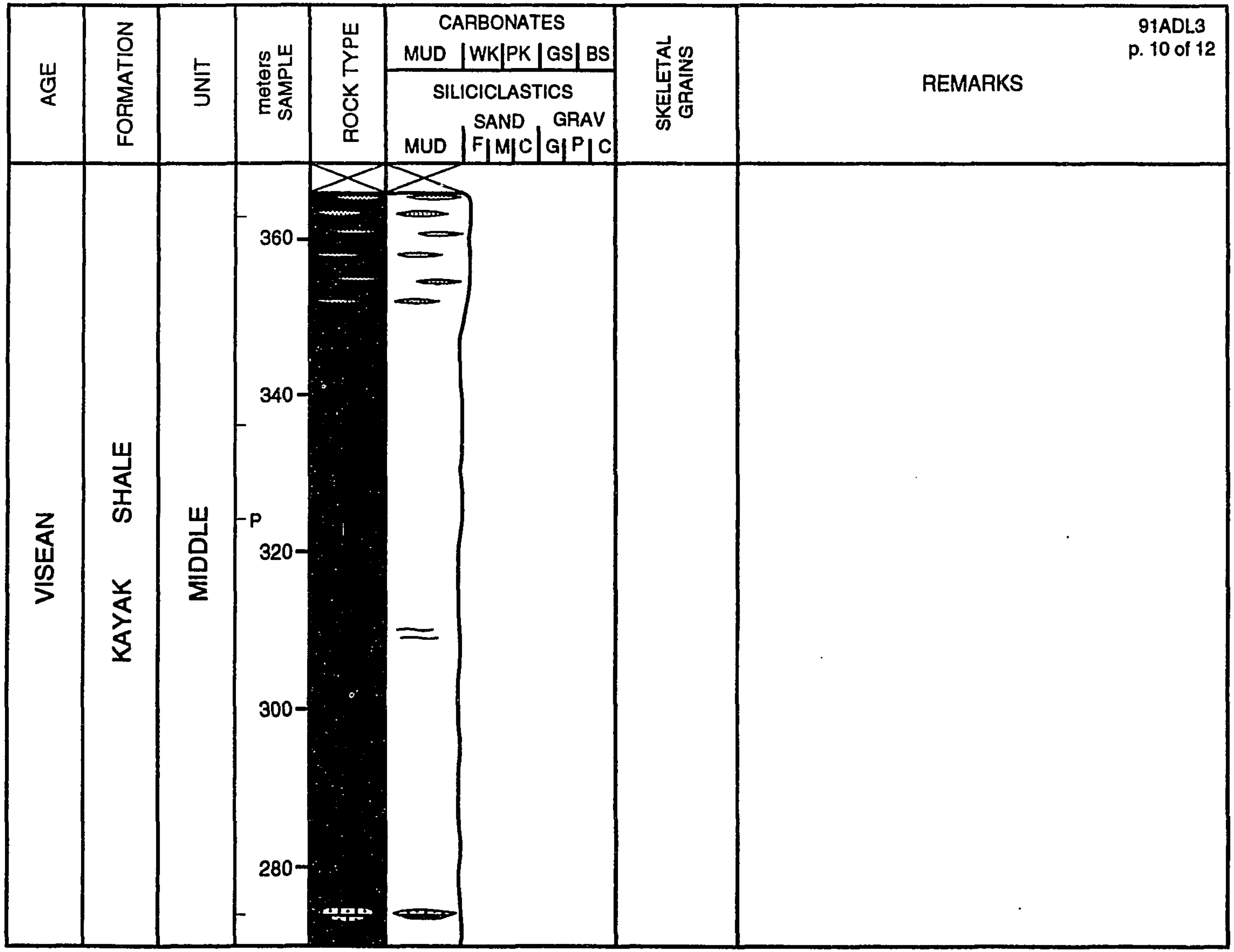
248 - ~366 m
Shale, silty shale, and siltstone; dark gray-to-black, fissile; siltsotne above sandstone body at 248 passes gradually into silty shale and shale; minor lenticular-lamina of fine-grained sandstone in shale; top of succession in covered with limestone talus of upper Kayak Shale and Lisburne Group. Deposited in low-energy marine setting with anaerobic to dysaerobic bottom water conditions, below fairweather wave-base.

237.5 - 248 m
Coarse-grained sandstone and granule conglomerate; moderate-to well-sorted quartzarenite; clast-supported, chert and quartz granule conglomerate; sandstone and conglomerate is thick-bedded and consists of large-scale trough cross-statification and minor horizontal stratification, foresets and horizontal laminae commonly separated by thin shale parting, horizontal bedding at top of interval contains locally occurring low-angle inclined lamina. Deposited in shallow, migrating tidal inlet. Inlet cut through barrier-island. Sand body has been traced to Curve Creek ~6.0 km west, where it is 2to 7 m thick and consists of tidal channel-fill and barrier beach deposits.



AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD
WK
PK
GS
BS
SILICICLASTICS
SAND
GRAV
MUD
F
M
C
G
P
C
SKELETAL GRAINS
REMARKS
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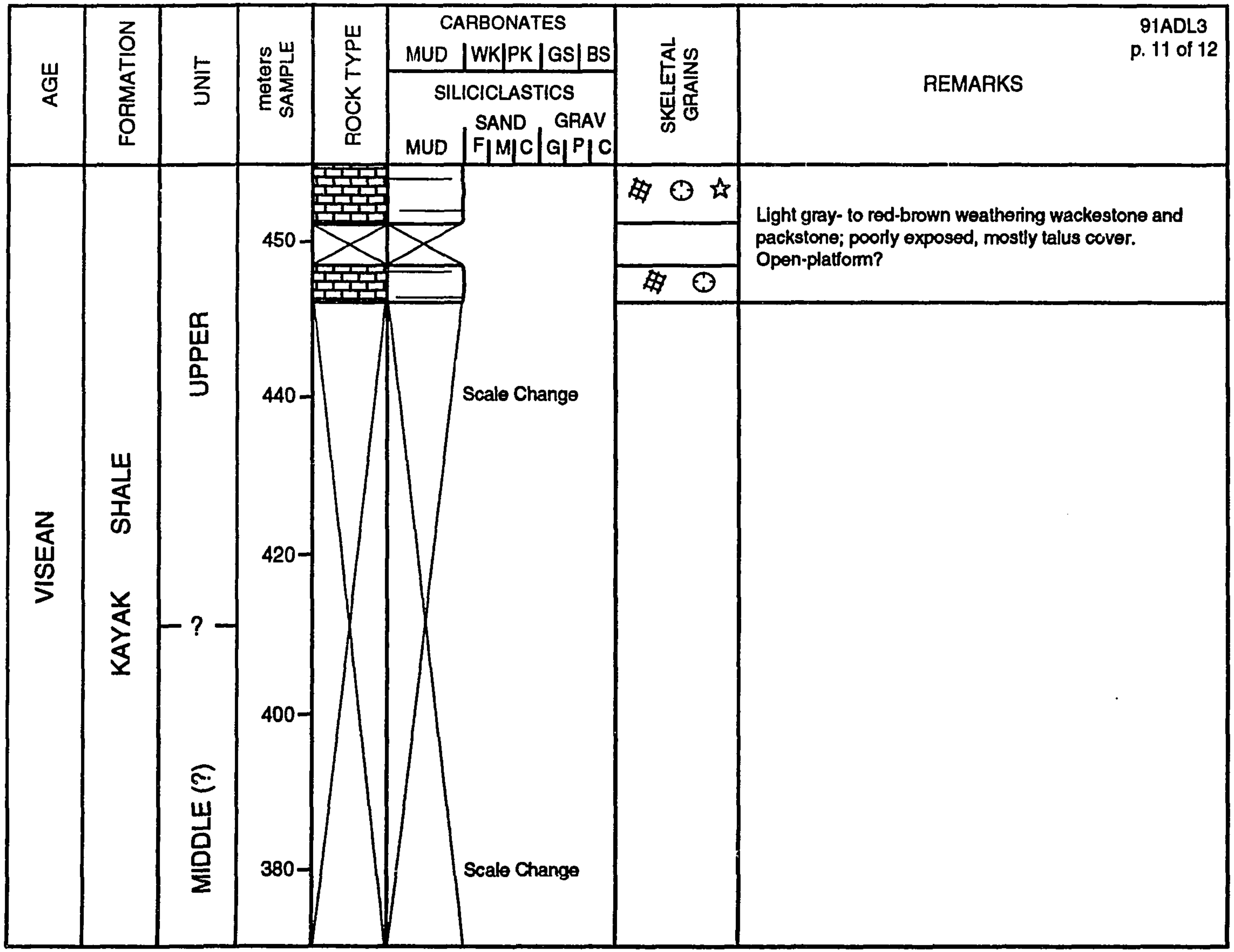
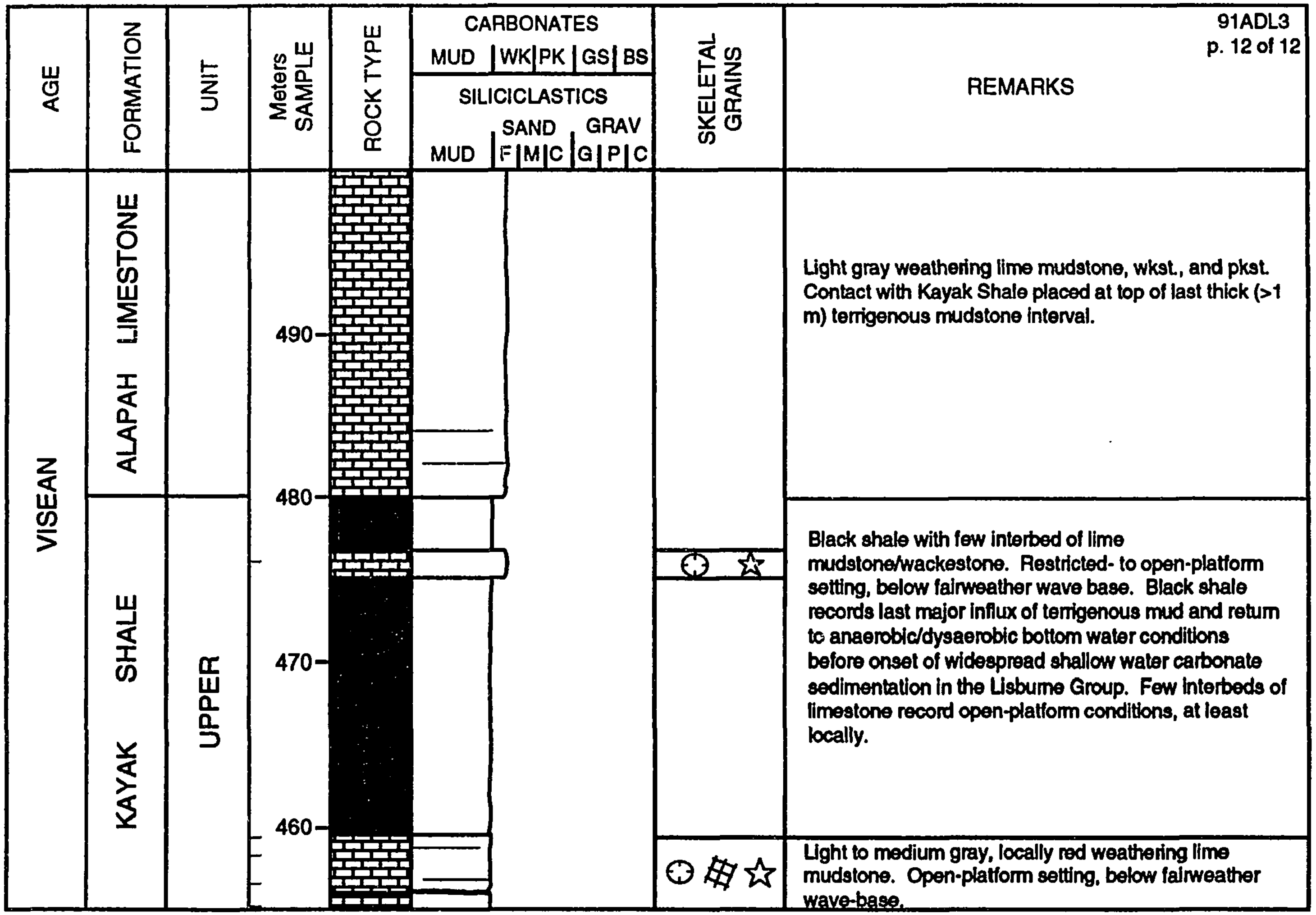
VISEAN
KAYAK SHALE
MIDDLE
360
340
P
320
300
280


91ADL3
p. 11 of 12
AGE
FORMATION
UNIT
meters
SAMPLE
ROCK TYPE
CARBONATES
MUD WK PK GS BS
SILICICLASTICS
SAND GRAV
MUD F M C G P C
SKELETAL GRAINS
REMARKS
VISEAN
KAYAK SHALE
UPPER
?
MIDDLE (?)
450
440
420
400
380
Scale Change
Scale Change
Light gray- to red-brown weathering wackestone and packstone; poorly exposed, mostly talus cover. Open-platform?


91ADL3
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AGE
FORMATION
UNIT
Meters
SAMPLE
ROCK TYPE
CARBONATES
MUD
WK
PK
GS
BS
SILICICLASTICS
MUD
SAND
F
M
C
GRAV
G
P
C
SKELETAL GRAINS
REMARKS
VISEAN
ALAPAH LIMESTONE
KAYAK SHALE
UPPER
490
480
470
460
Light gray weathering lime mudstone, wkst., and pkst. Contact with Kayak Shale placed at top of last thick (>1 m) terrigenous mudstone interval.
Black shale with few interbed of lime mudstone/wackestone. Restricted- to open-platform setting, below fairweather wave base. Black shale records last major influx of terrigenous mud and return tc anaerobic/dysaerobic bottom water conditions before onset of widespread shallow water carbonate sedimentation in the Lisburne Group. Few interbeds of limestone record open-platform conditions, at least locally.
Light to medium gray, locally red weathering lime mudstone. Open-platform setting, below fairweather wave-base.

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